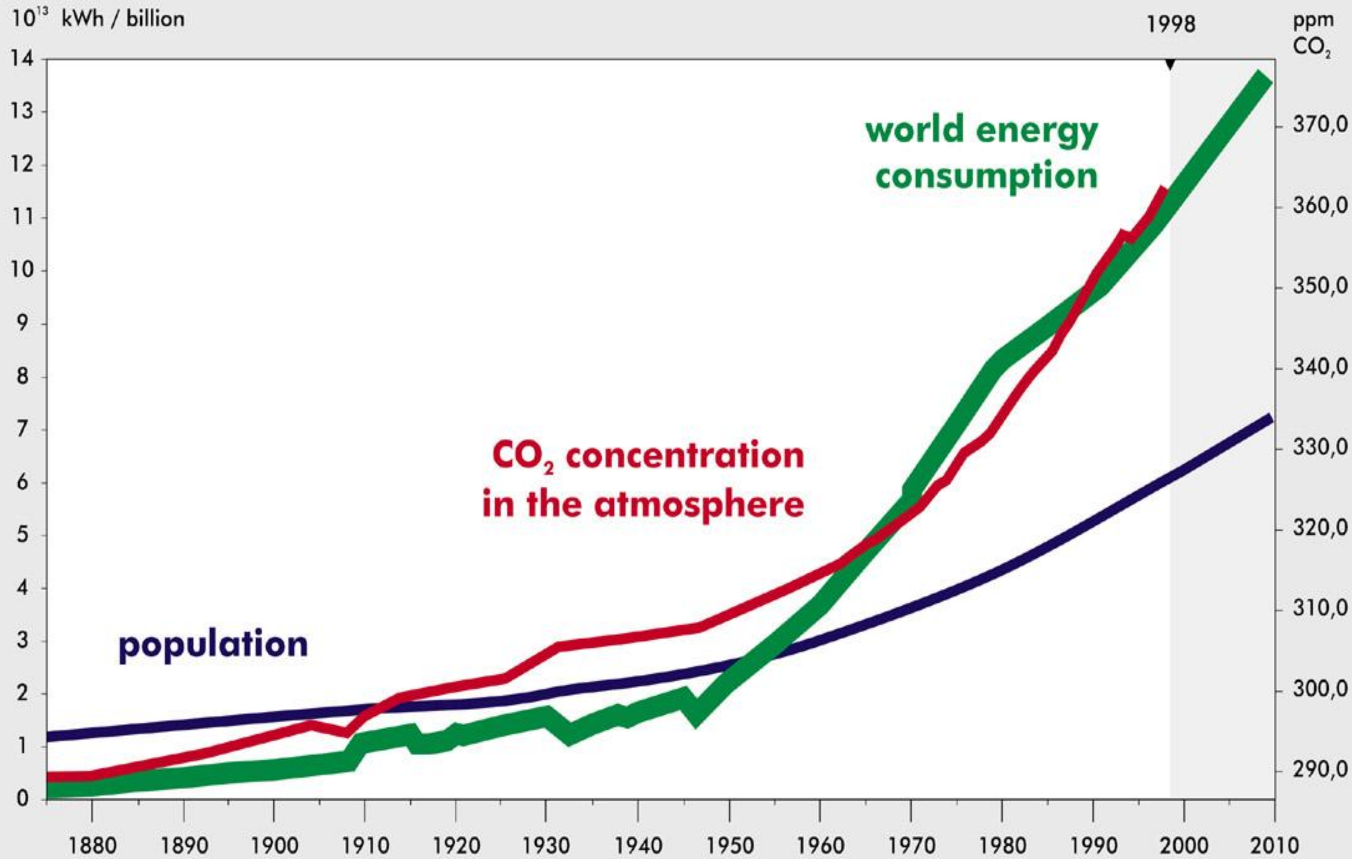
Solar Energy Exploitation Systems

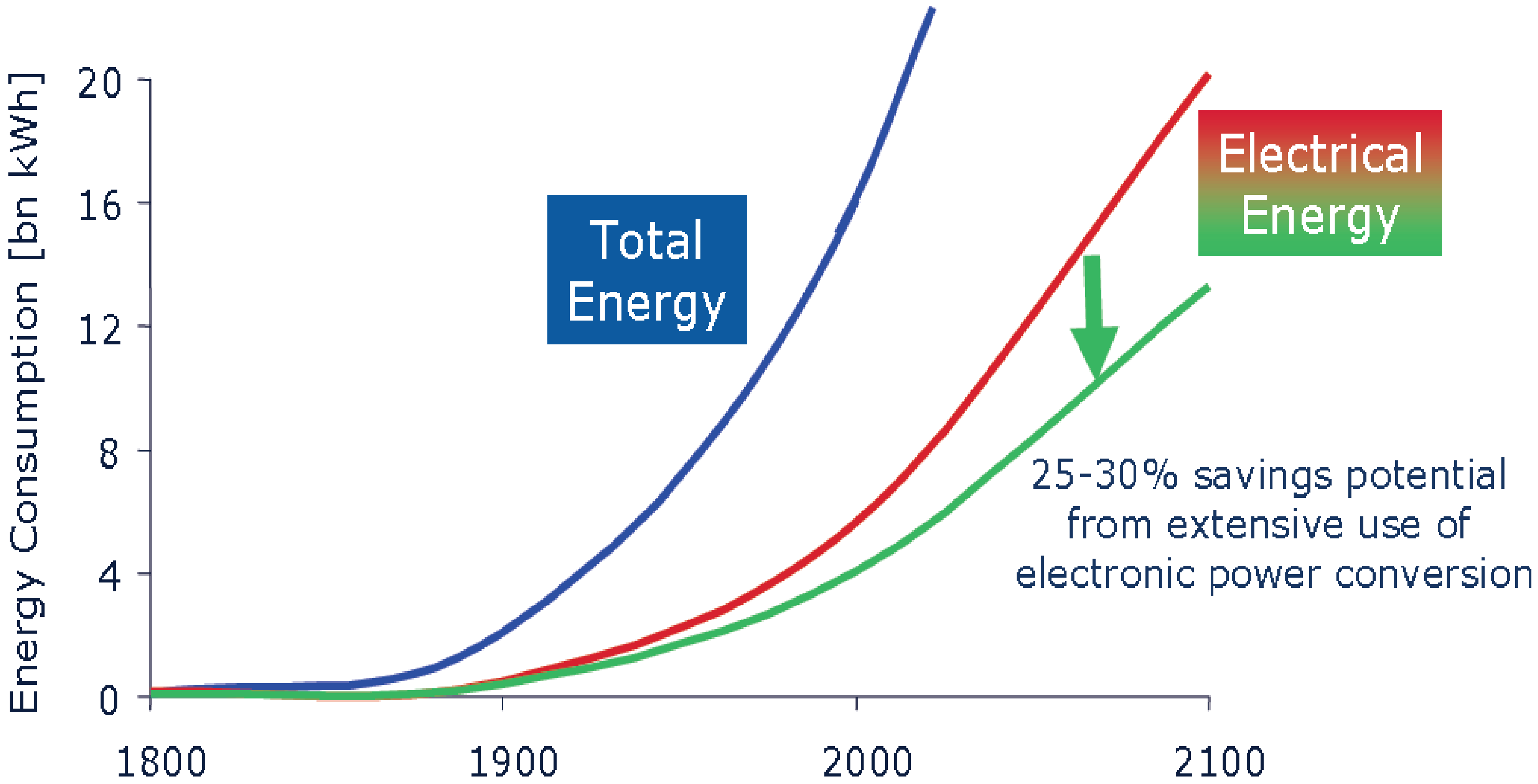
Course structure - lectures

1. Solar energy and basic forms of its exploitation
2. Photovoltaic phenomena
3. Solar cells and their characteristics
4. Monocrystalline, polycrystalline and thin film solar cells
5. Solar cells from other semiconductor materials
6. Construction and fabrication of solar cells
7. Construction and fabrication of modules
8. Basic types of photovoltaic systems
9. Energy storage for photovoltaic systems
10. Stand alone and on-grid systems
11. Applications of Photovoltaic systems
12. Basic economic and ecological aspects
13. Solar thermal systems
14. Conversion solar energy to electrical energy



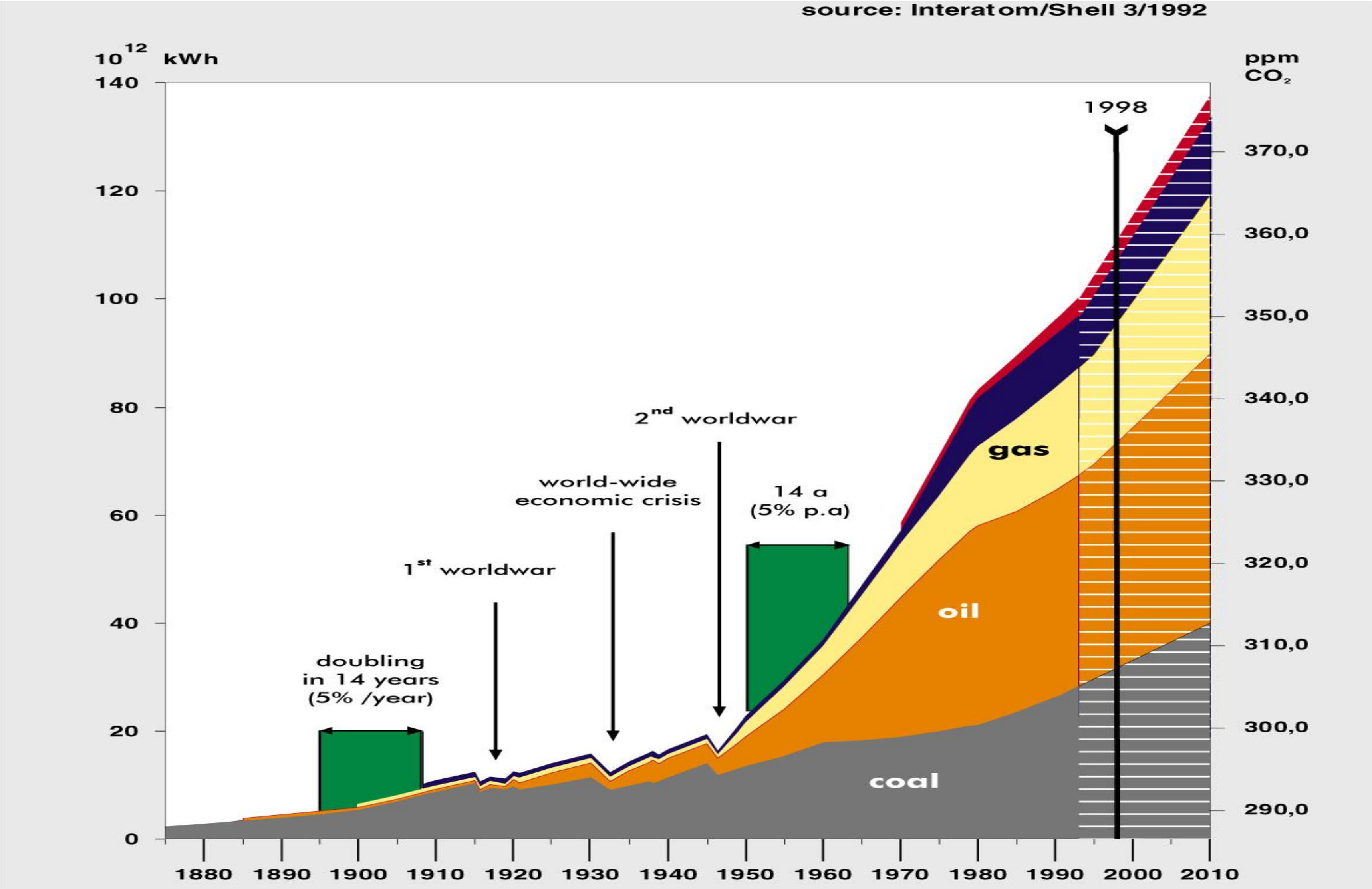
Growth rates for population, energy consumption and CO_2 concentration in the atmosphere

ISET

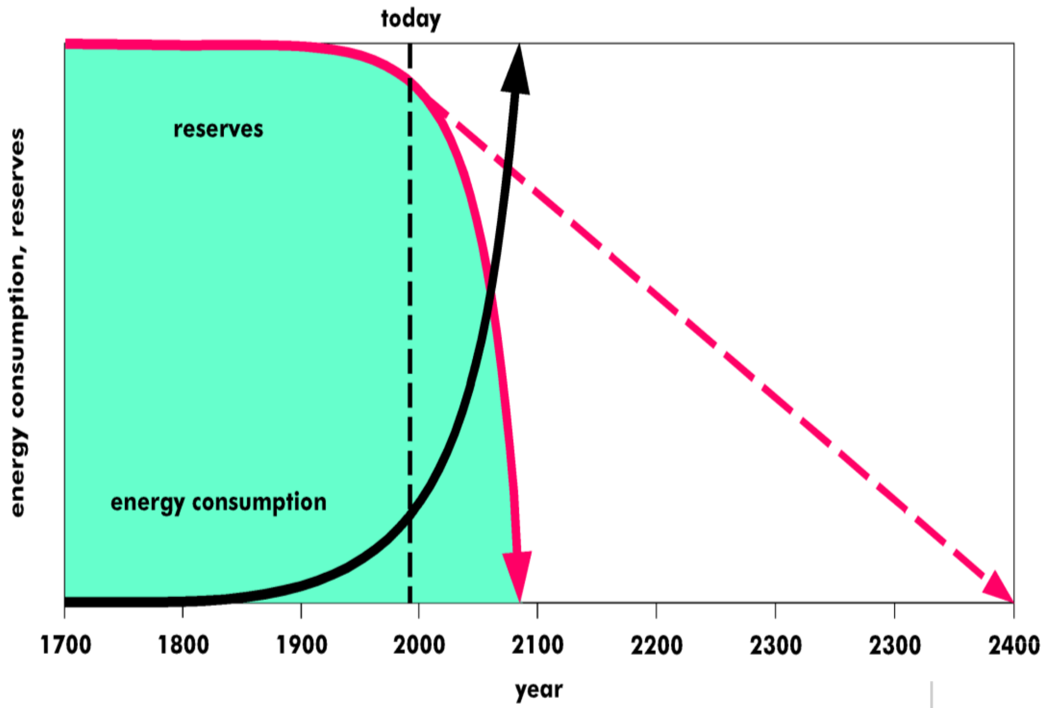


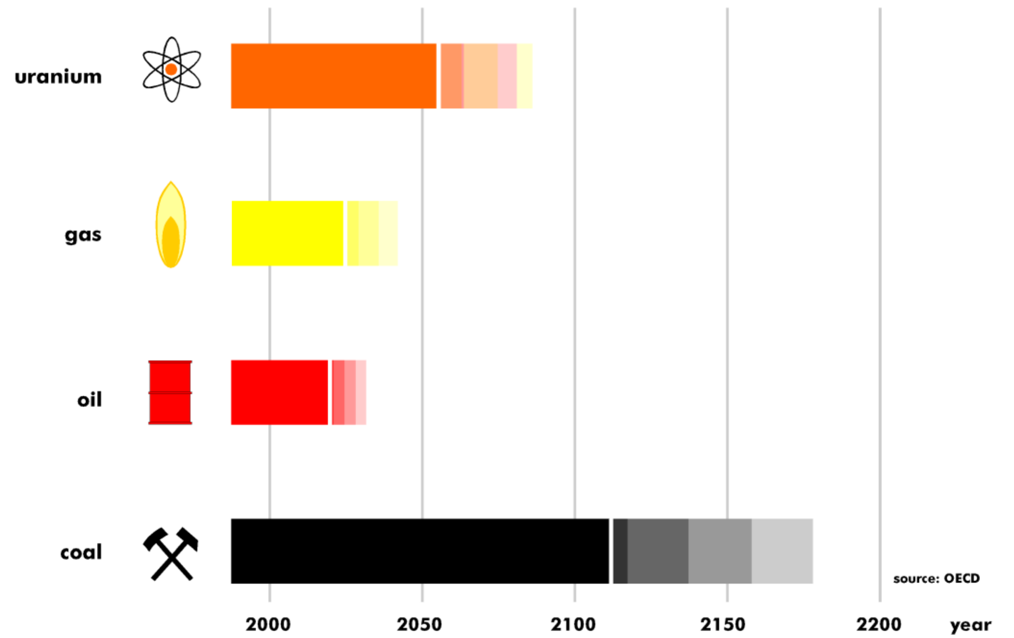
Energy Demand increases at 2.6 % annually

Source: Fraunhofer Institute, IISP, flyer, 2004

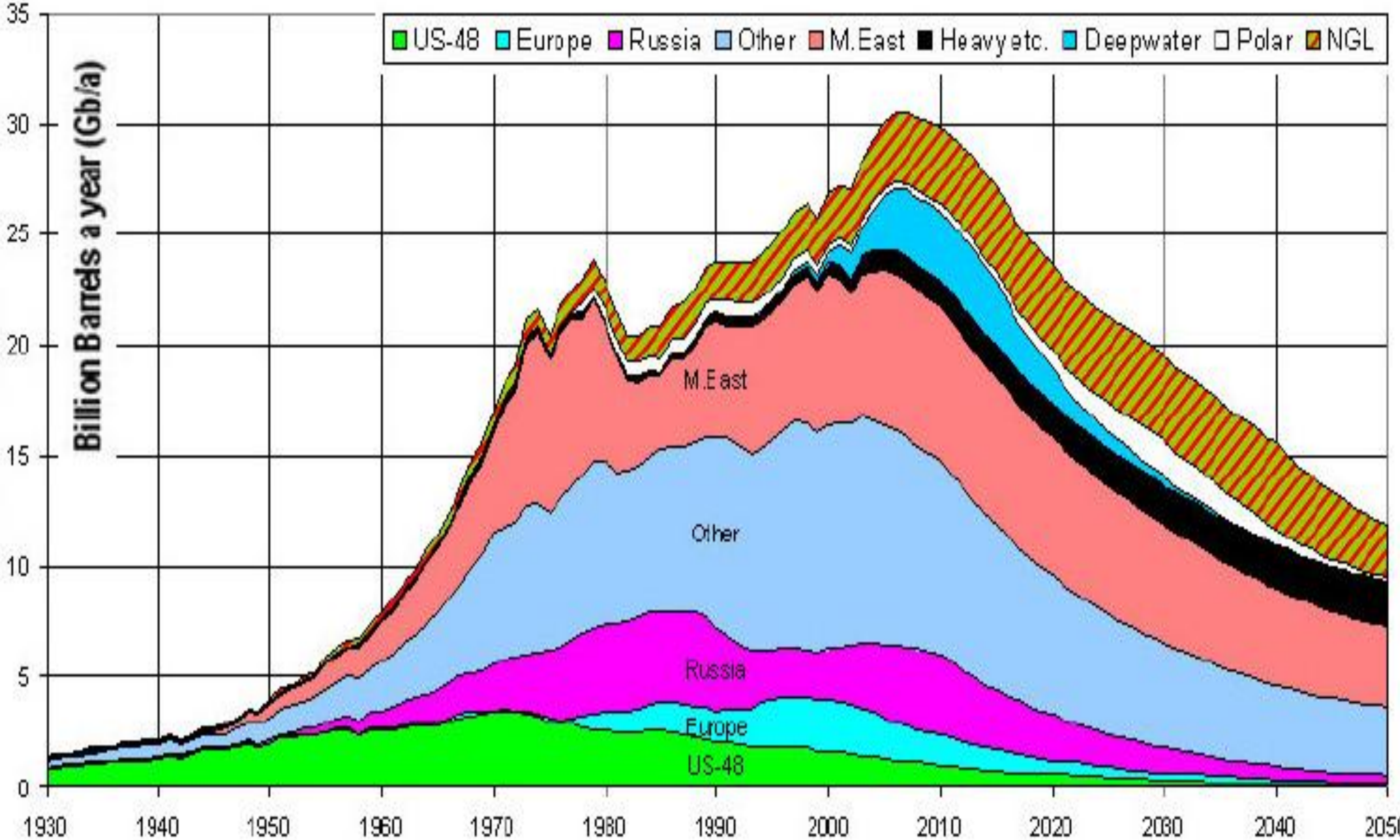


source: Interatom/Shell 3/1992
10^{12} kWh
ppm CO_2
140
120
100
80
60
40
20
0
370,0
360,0
350,0
340,0
330,0
320,0
310,0
300,0
290,0
1998
gas
2nd worldwar
world-wide economic crisis
14 a (5% p.a)
1st worldwar
oil
doubling in 14 years (5% /year)
coal
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010

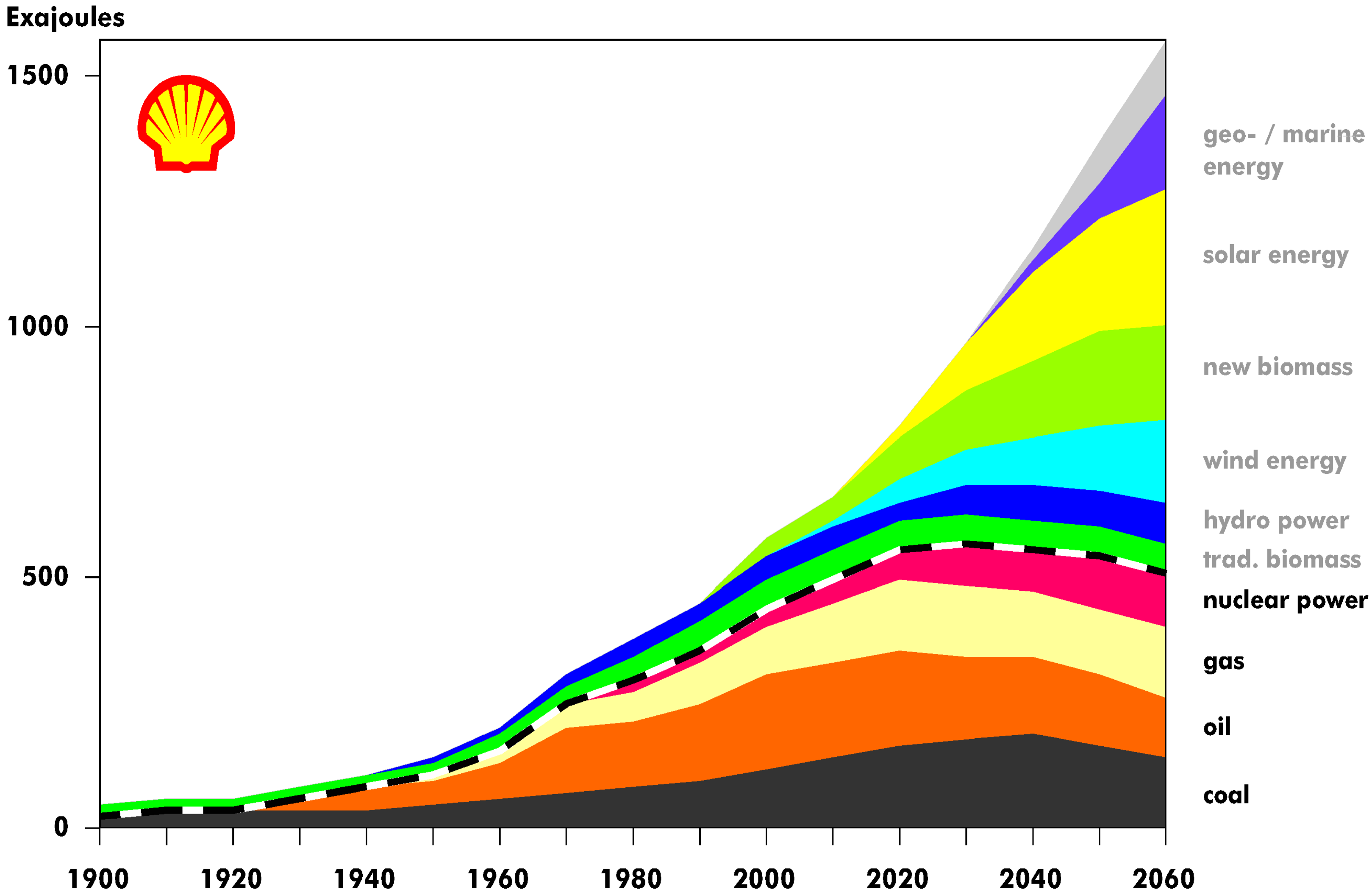




Scarcity of different energy sources

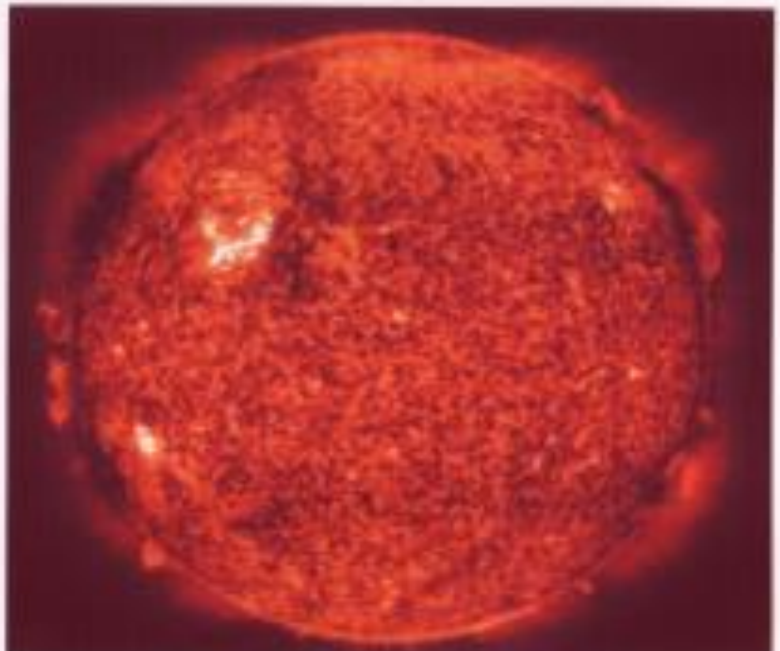


US-48
Europe
Russia
Other
M.East
Heavy etc.
Deepwater
Polar
NGL
Billion Barrels a year (Gb/a)
35
30
25
20
15
10
5
0
M.East
Other
Russia
Europe
US-48
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050



Exajoules
1500
1000
500
0
1900
1920
1940
1960
1980
2000
2020
2040
2060
geo- / marine energy
solar energy
new biomass
wind energy
hydro power
trad. biomass
nuclear power
gas
oil
coal

The Sun



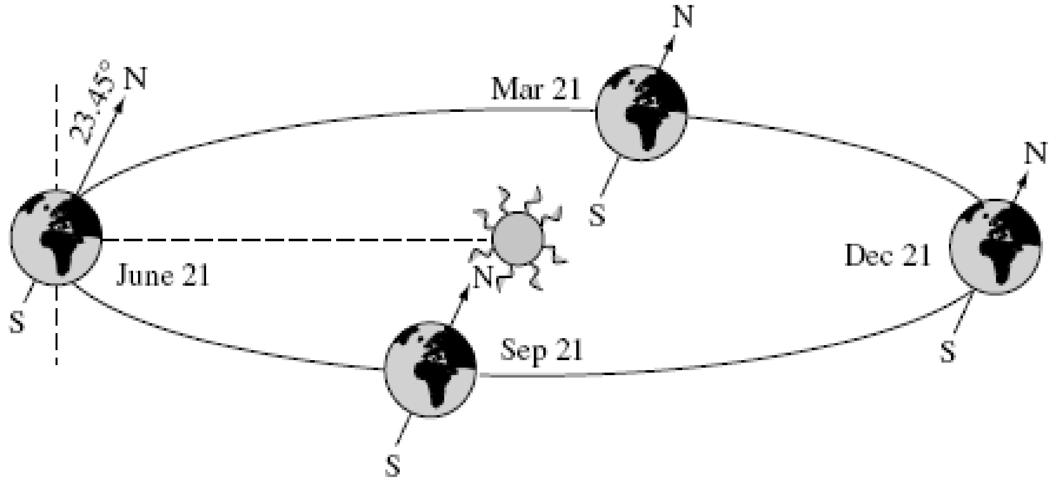
$r_S = 0.695 \times 10^9$ m

Surface temperature ~ 6000 K

Distance from the Earth

$R = 1.496 \times 10^{11}$ m (± 1.7%)

Energy of Solar Radiation

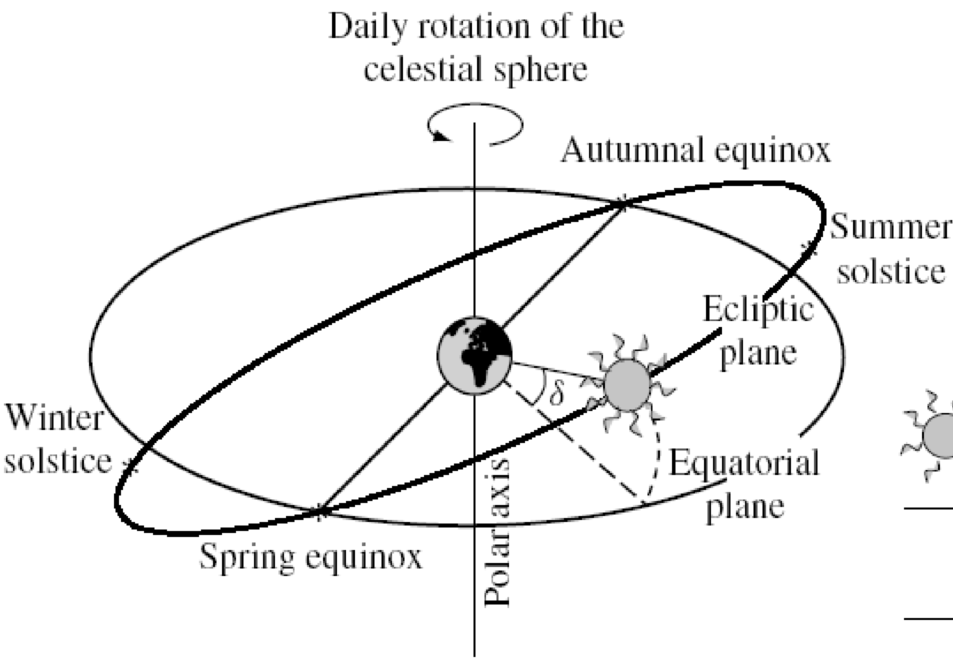


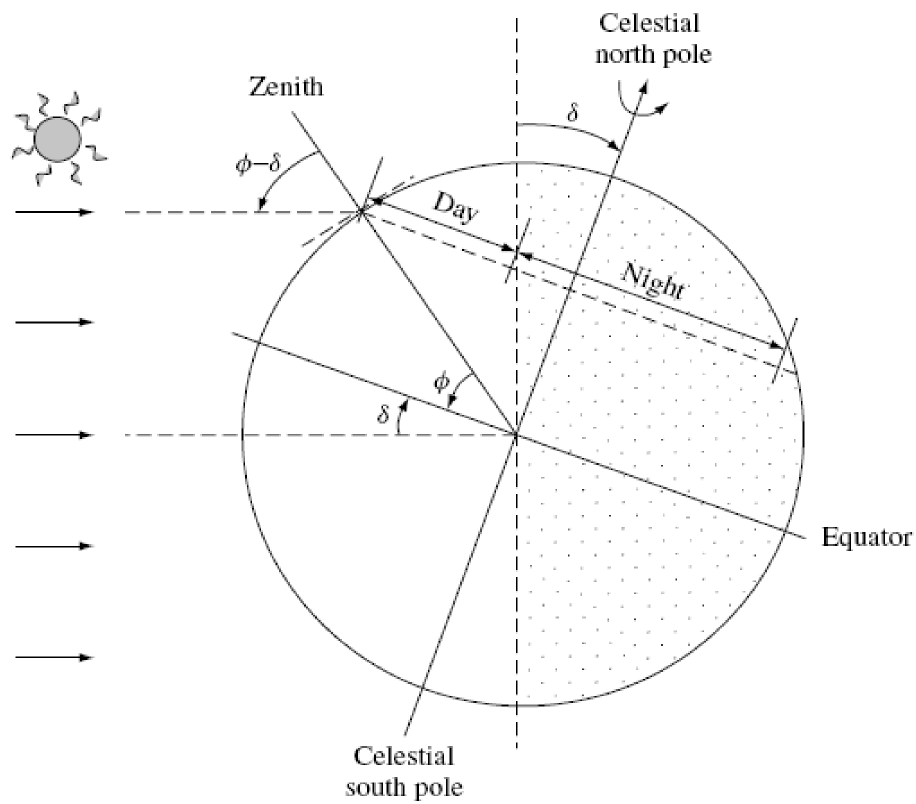
$$r = r_0 \left[1 + 0.017 \sin \left(\frac{360(d_n - 93)}{365} \right) \right]$$

$r_0 = 1.496 \times 10^8$ km

excentrita

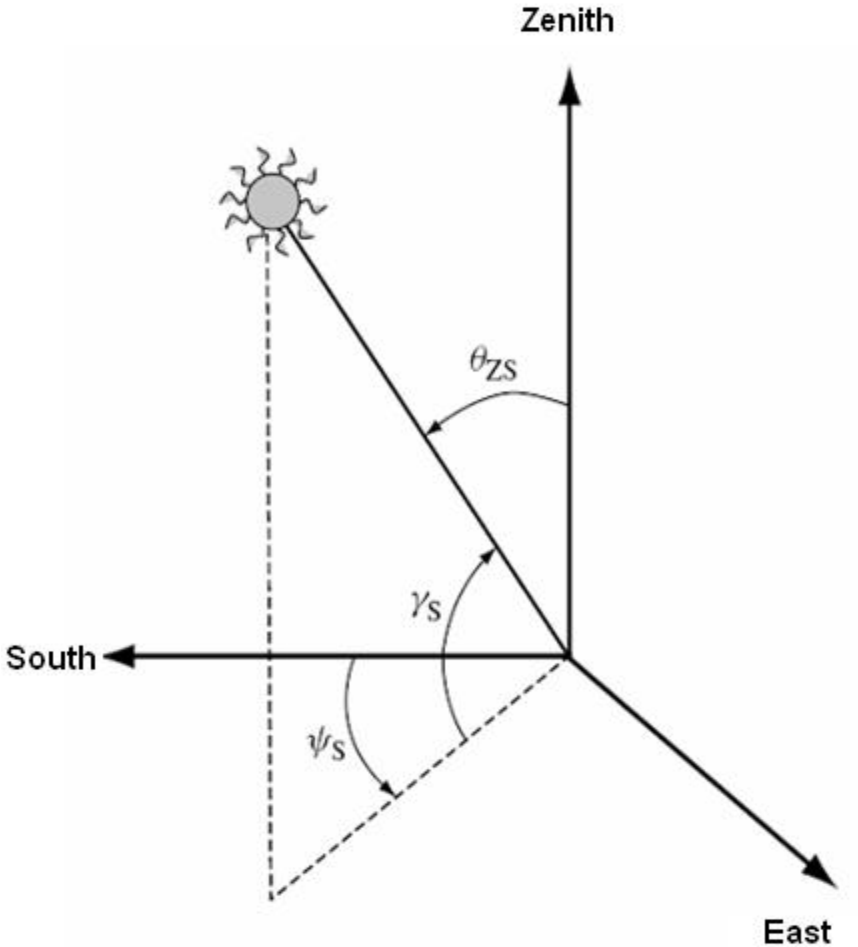
$$\varepsilon_0 = (r_0/r)^2 = 1 + 0.033 \cos \left(\frac{360 d_n}{365} \right)$$





solar declination δ.

$$\delta = 23.45^\circ \sin\left[\frac{360(d_n + 284)}{365}\right]$$



zenith angle, $\boldsymbol{\theta}_{\mathbf{ZS}}$

solar azimuth, $\boldsymbol{\psi}_{\mathrm{S}}$,

solar altitude, $\boldsymbol{\gamma}_{\mathbf{S}}$

geographic latitude, Φ

$$\cos\theta_{ZS} = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega = \sin\gamma_S$$

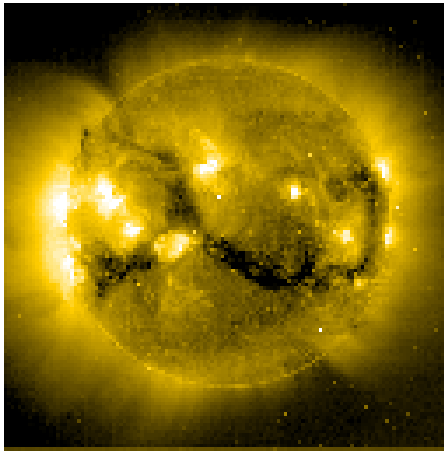
$$\cos\psi_S = \frac{(\sin\gamma_S\sin\phi - \sin\delta)}{\cos\gamma_S\cos\phi}[\mathrm{sign}(\phi)]$$

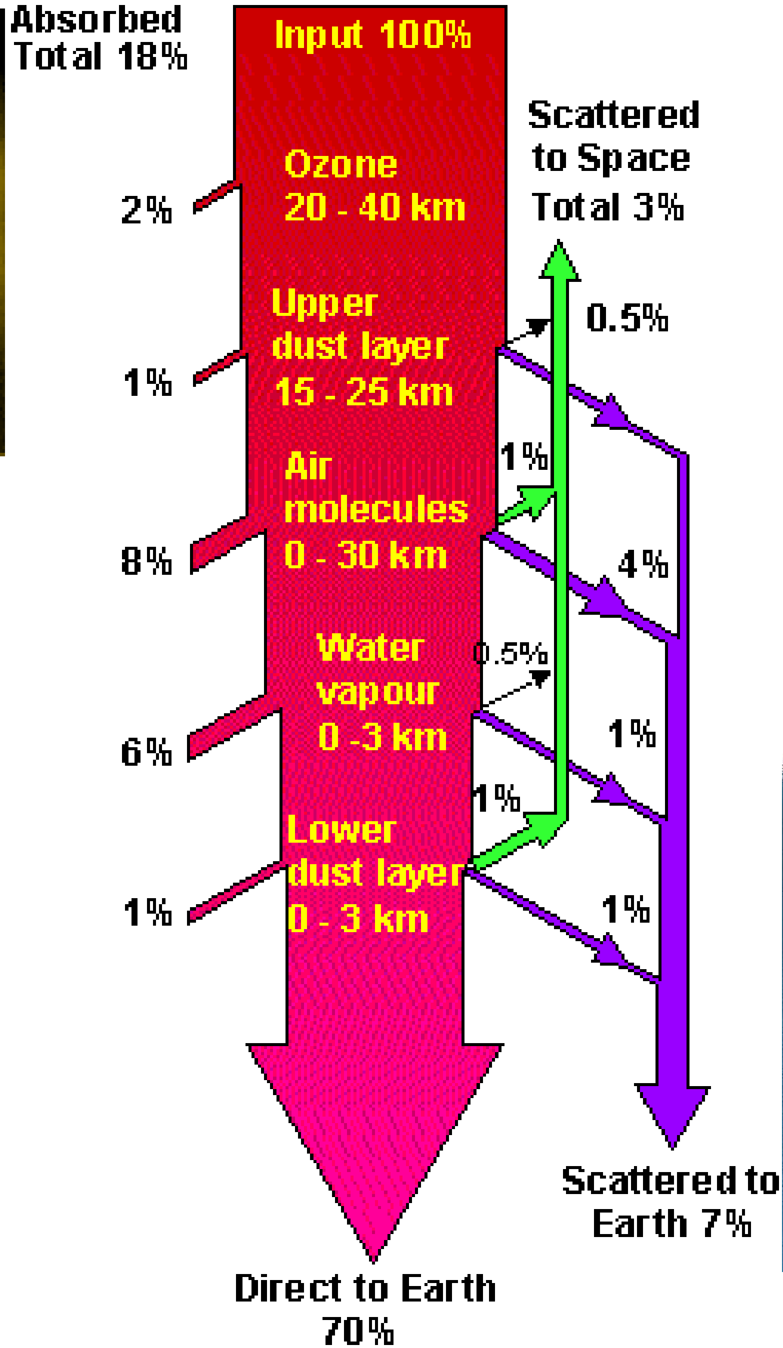
sunrise angle, ω_S,

$$\omega_S = -\arccos(-\tan\delta\tan\phi)$$

Declination and extraterrestrial irradiation values for the characteristic day of each month

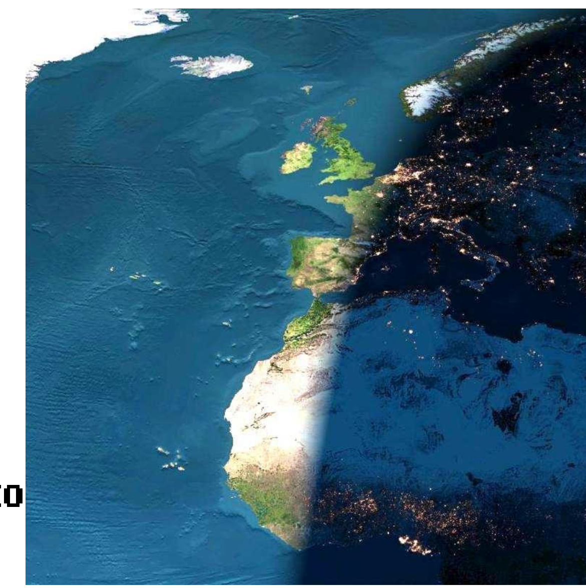
Month	Date	d_n	δ [degrees]	$B_{0d}(0) = B_{0dm}(0)$, in [Wh/m^2]			
				$\phi = 30°$	$\phi = 60°$	$\phi = -30°$	$\phi = -60°$
January	17	17	−20.92	5 907	949	11 949	11 413
February	14	45	−13.62	7 108	2 235	11 062	9 083
March	15	74	−2.82	8 717	4 579	9 531	5 990
April	15	105	+9.41	10 225	7 630	7 562	3 018
May	15	135	+18.79	11 113	10 171	5 948	1 225
June	10	161	+23.01	11 420	11 371	5 204	605
July	18	199	+21.00	11 224	10 741	5 530	878
August	18	230	+12.78	10 469	8 440	6 921	2 294
September	18	261	+1.01	9 121	5 434	8 835	4 937
October	19	292	−11.05	7 436	2 726	10 612	8 226
November	18	322	−19.82	6 056	1 114	11 754	10 983
December	13	347	−23.24	5 498	613	12 174	12 177

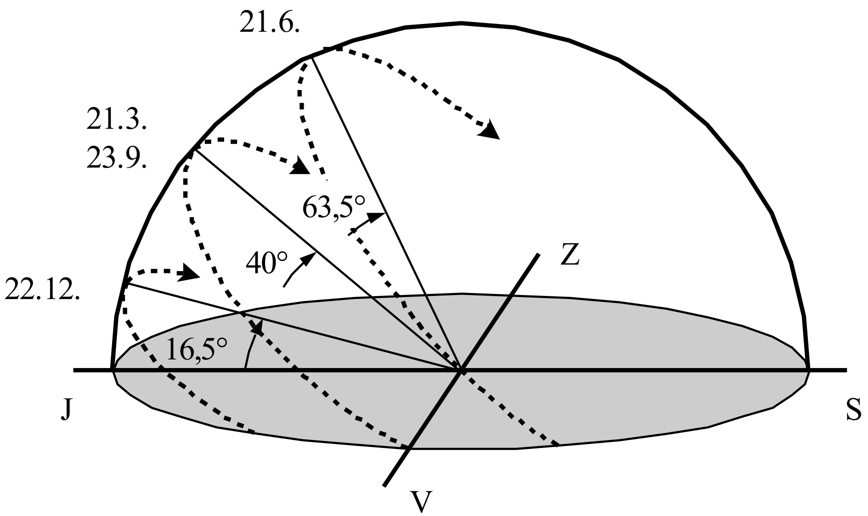




1000W/m^2

1 – 6MWh/m^2

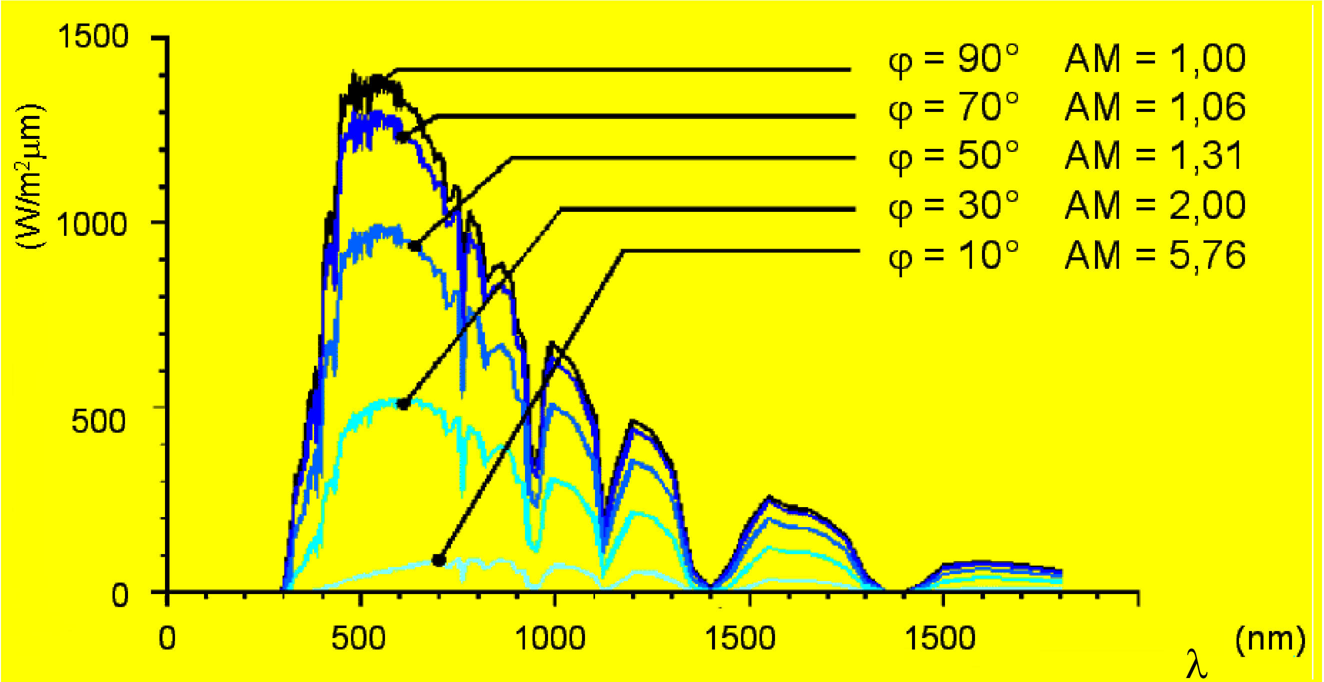


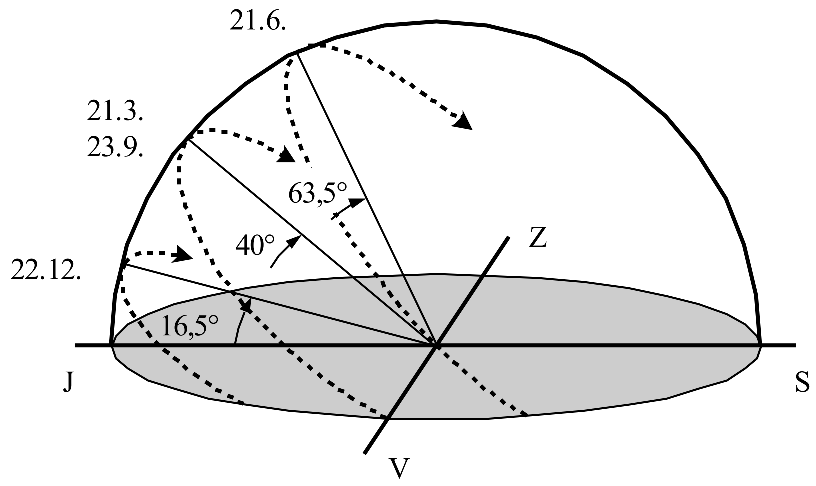


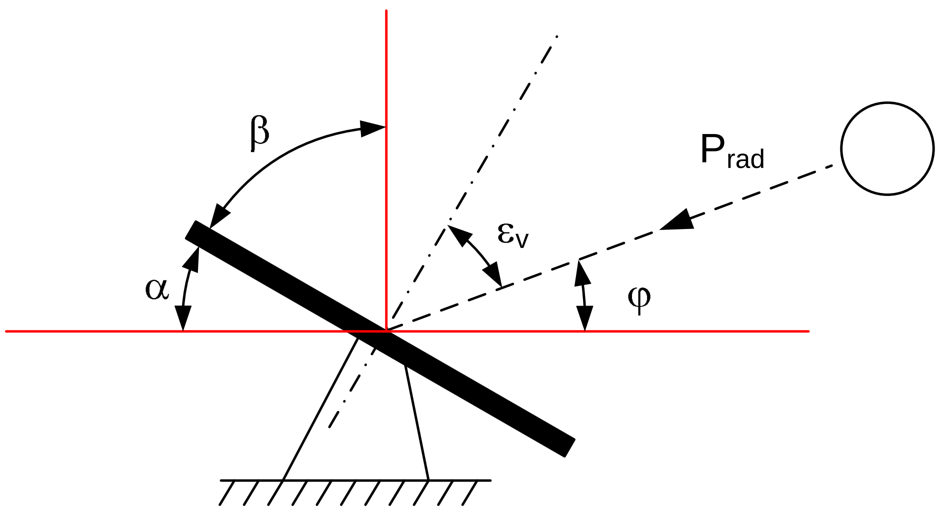
$$B(\varphi) = B_0 (0{,}7)^{AM}$$

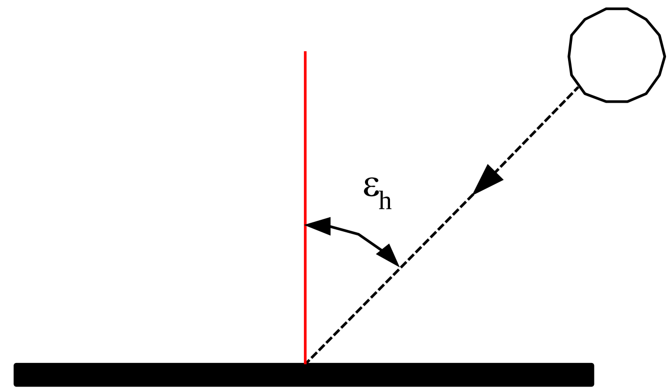
$$AM = \frac{1}{\sin\varphi}$$

Atmospheric Mass coefficient







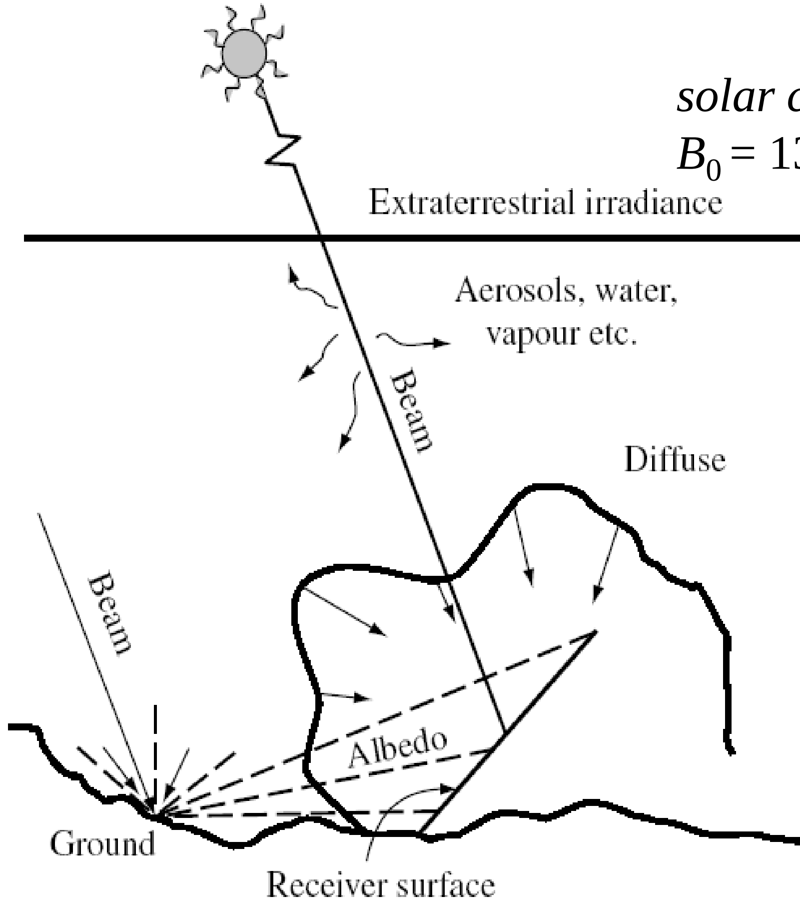


$$P_u(t) = 1367 \times 0.7^{\frac{1}{\sin\varphi(t)}} \cos\varepsilon_v(t)\cos\varepsilon_h(t)$$

$$W_u = \int_{SR}^{SS} 1367 \times 0.7^{\frac{1}{\sin\varphi(t)}} \cos\varepsilon_v(t)\cos\varepsilon_h(t)dt$$

Irradiance means density of power falling on a surface, and is measured in W/m^2

solar constant
$B_0 = 1367\ W/m^2$



beam radiation, made up of beams of light that are not reflected or scattered - ***B***

diffuse radiation, coming from the whole sky apart from the sun's disc- ***D***

albedo radiation is radiation reflected from the ground - ***R***

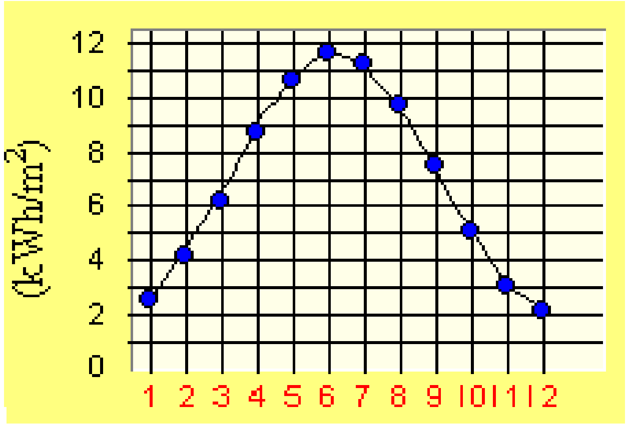
global radiation (direct + diffuse + albedo). ***G = B + D + R***

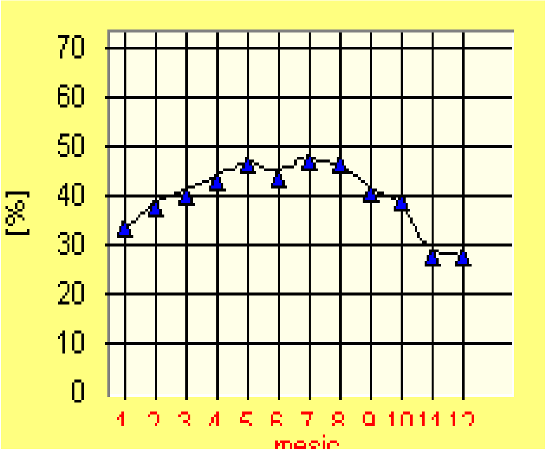
There are random variations caused by climatic conditions: cloud cover, dust storms and so on

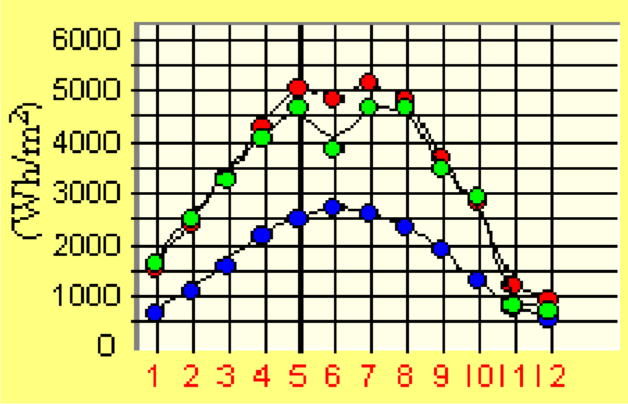
Monthly mean values of global horizontal daily irradiation, $\boldsymbol{G_{\mathrm{dm}}(0)}$

A *clearness index* $\boldsymbol{K_{\mathrm{Tm}}}$, (calculated for each month) gives a measure of the atmospheric transparency.

$$K_{\mathrm{Tm}} = \frac{G_{\mathrm{dm}}(0)}{B_{0\mathrm{dm}}(0)}$$





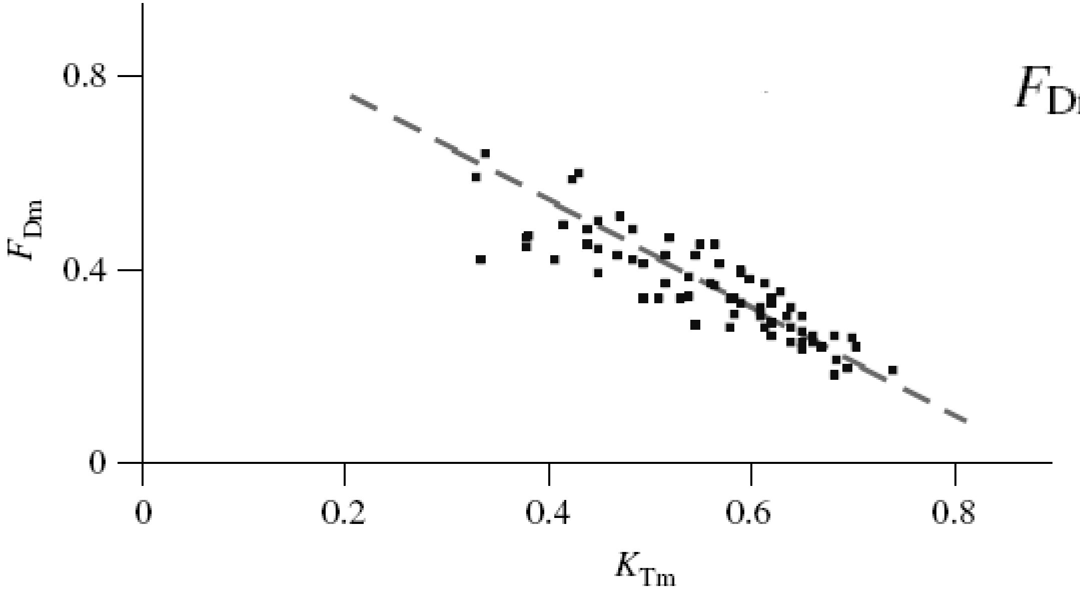


The diffuse fraction of the mean daily global irradiation

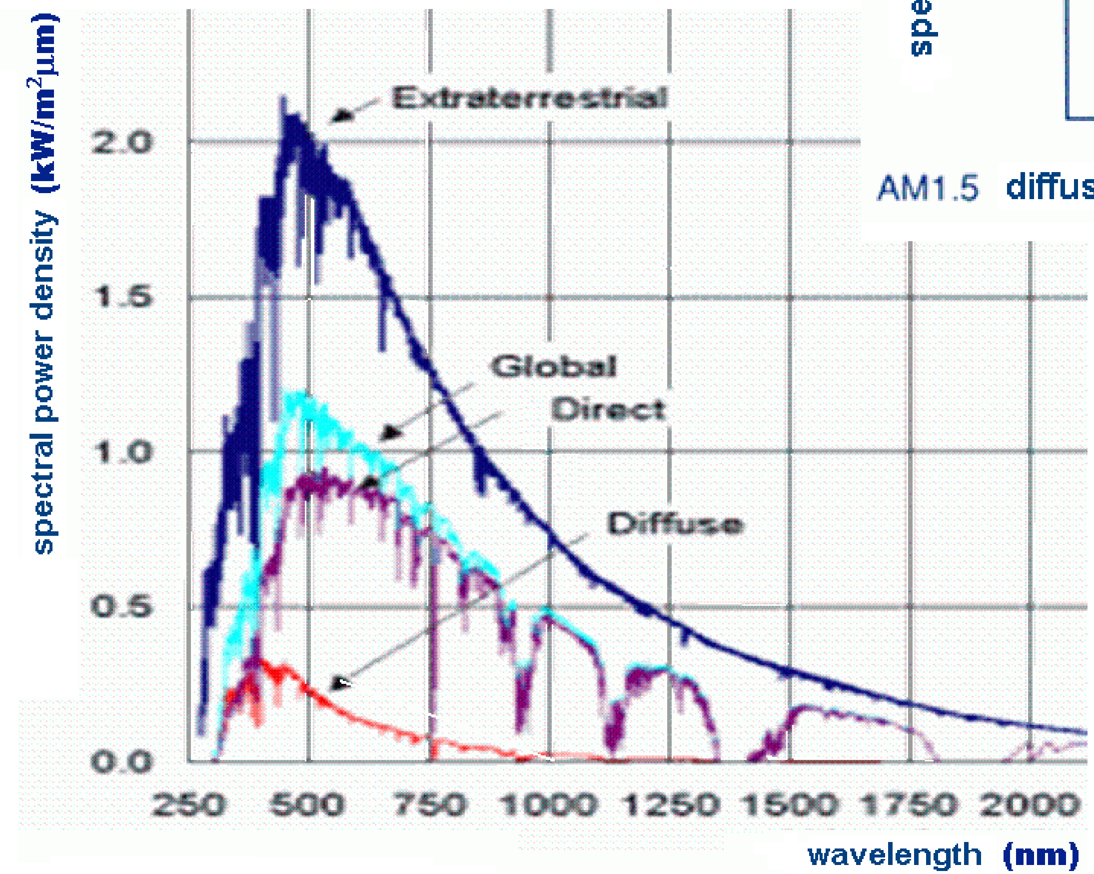
$$F_{Dm} = D_{dm}(0)/G_{dm}(0)$$

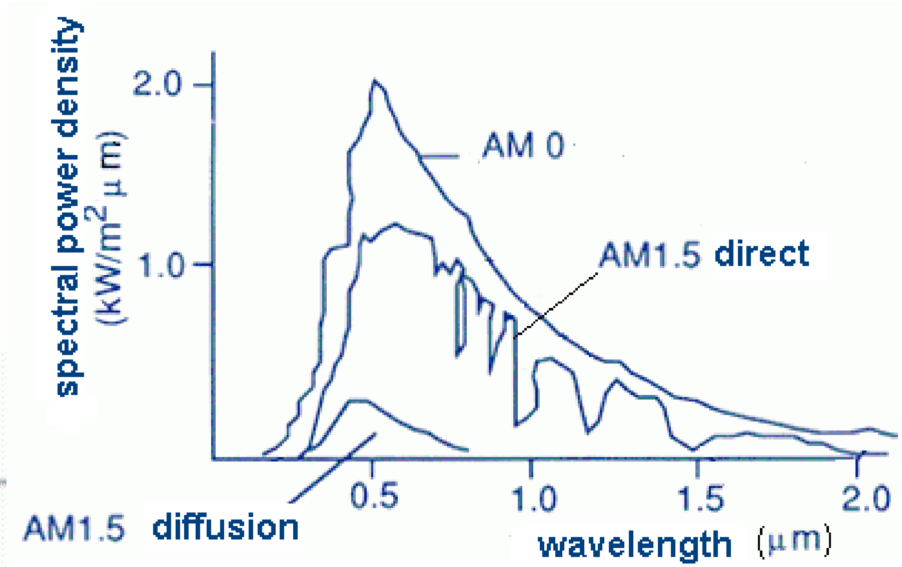
The clearness index

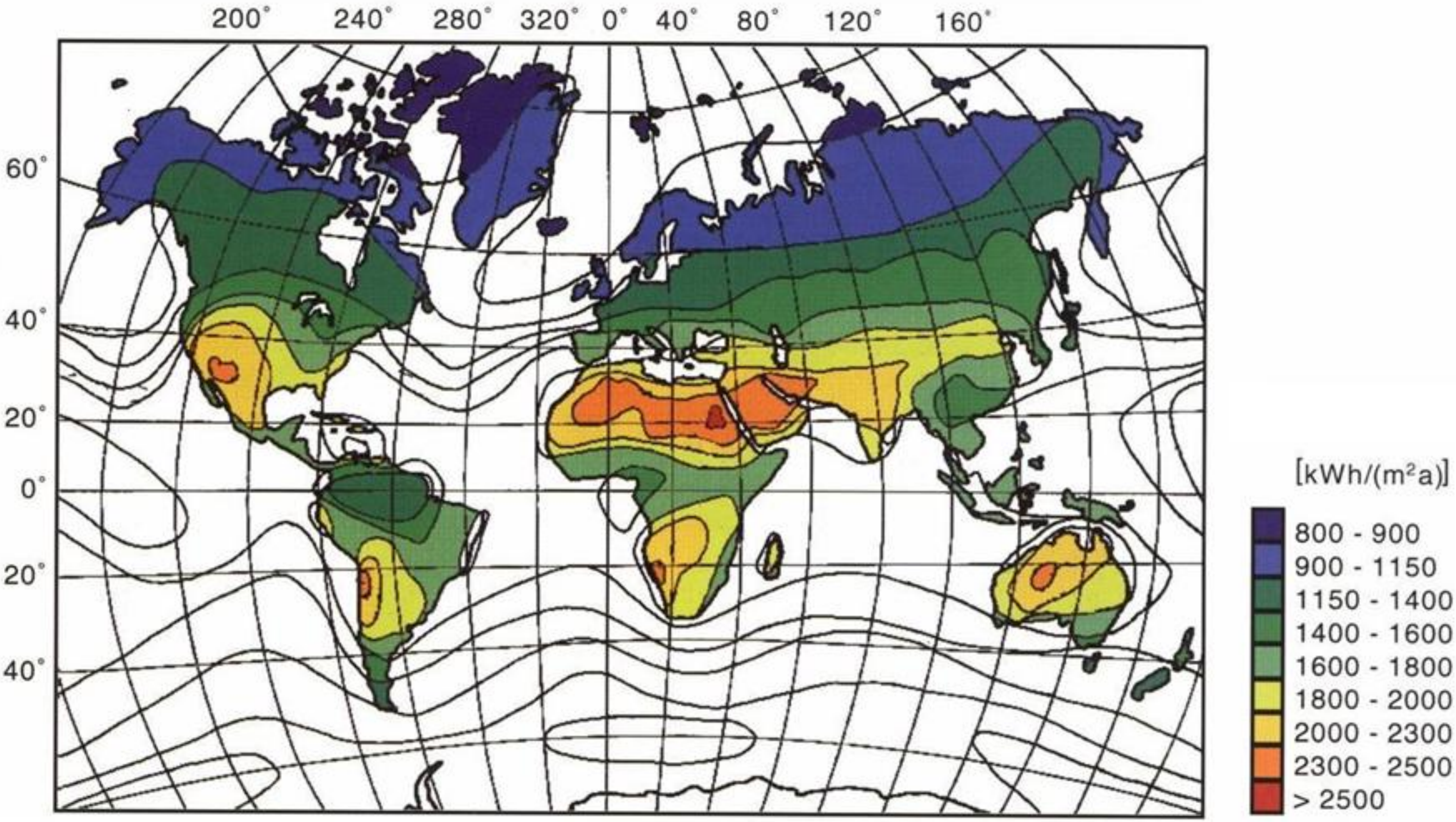
$$K_{Tm} = \frac{G_{dm}(0)}{B_{0dm}(0)}$$



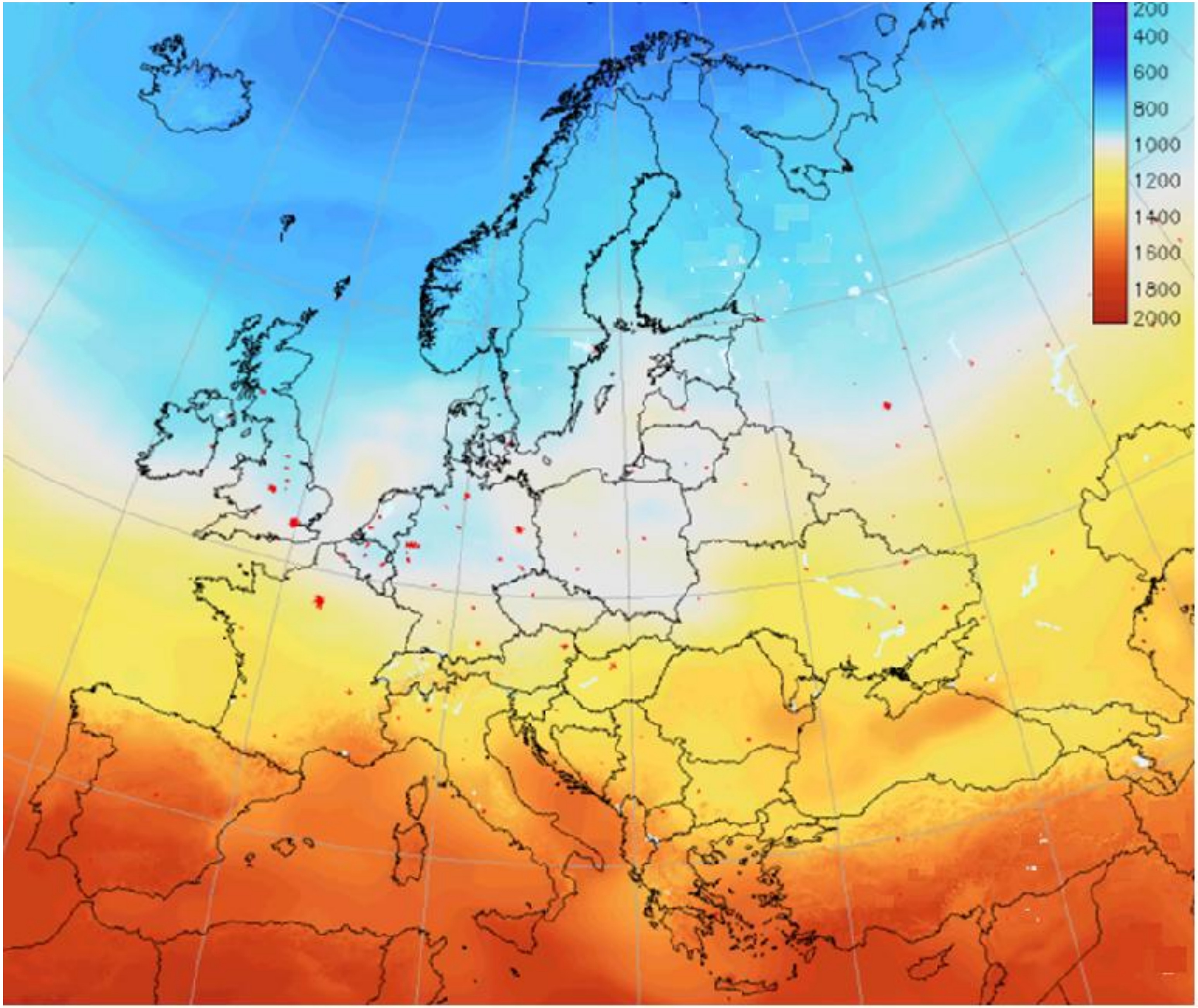
$$F_{Dm} = 1 - 1.13 K_{Tm}$$


spectral power density (kW/m²µm)
2.0
1.5
1.0
0.5
0.0
Extraterrestrial
Global
Direct
Diffuse
250
500
750
1000
1250
1500
1750
2000
wavelength (nm)

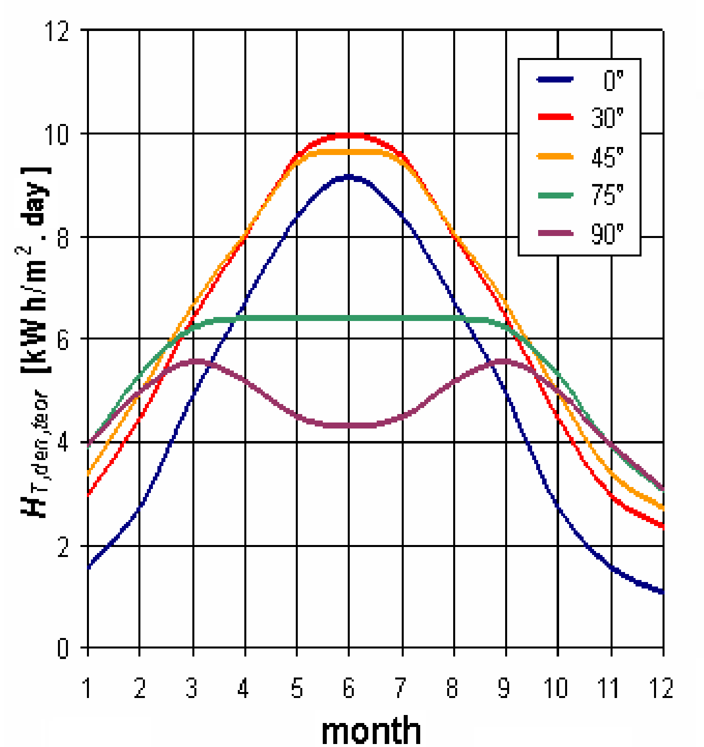

spectral power density
(kW/m² µ m)
2.0
1.0
AM 0
AM1.5 direct
AM1.5 diffusion
0.5
1.0
1.5
2.0
wavelength (µ m)



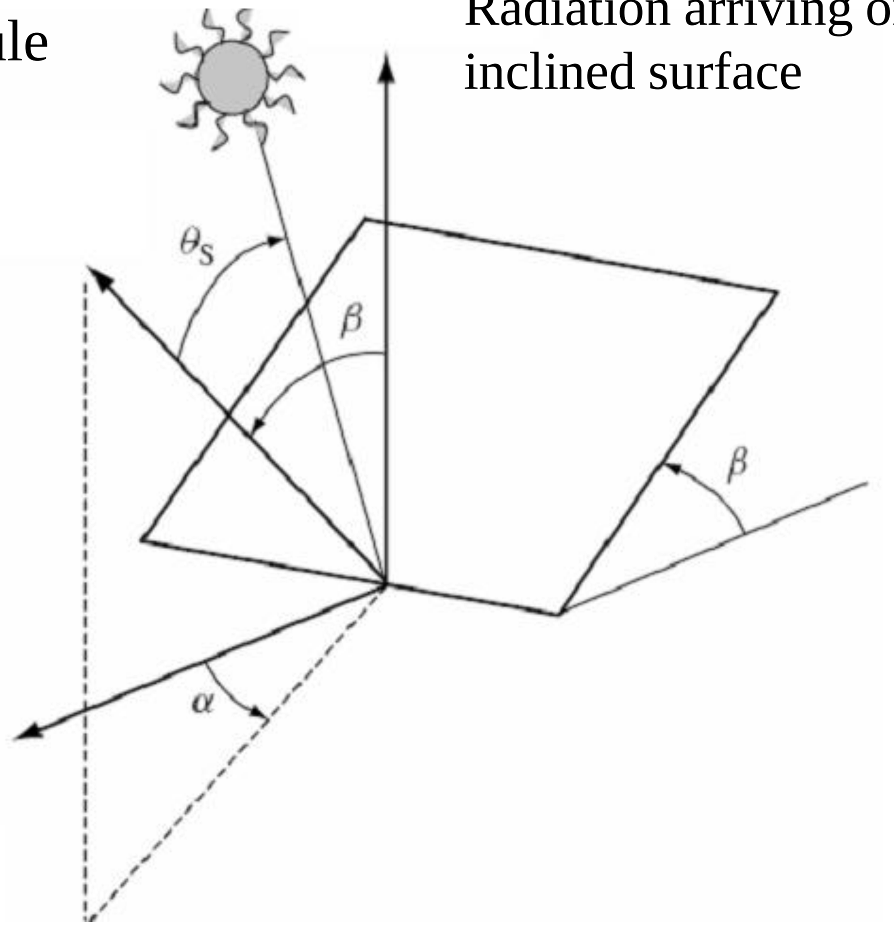
200°
240°
280°
320°
0°
40°
80°
120°
160°
60°
40°
20°
0°
20°
40°
[kWh/(m²a)]
800 - 900
900 - 1150
1150 - 1400
1400 - 1600
1600 - 1800
1800 - 2000
2000 - 2300
2300 - 2500
> 2500


200
400
600
800
1000
1200
1400
1600
1800
2000

Radiation arriving on PV module



Radiation arriving on an inclined surface

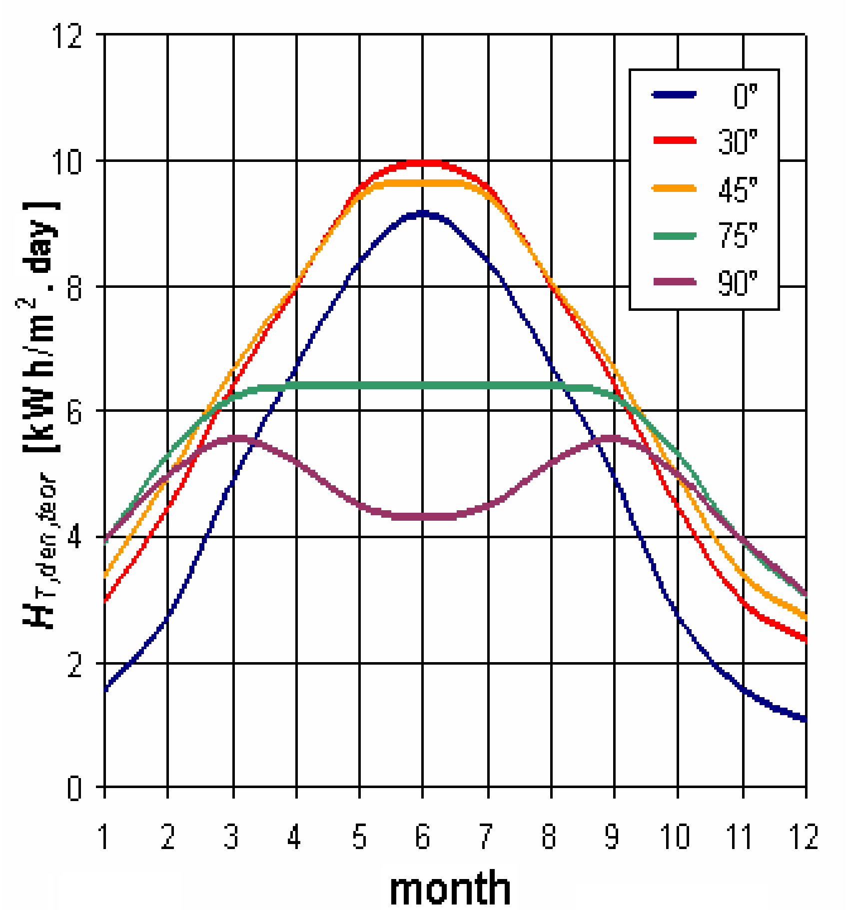


$$\cos\theta_S = \sin\delta\sin\phi\cos\beta - [\mathrm{sign}(\phi)]\sin\delta\cos\phi\sin\beta\cos\alpha + \cos\delta\cos\phi\cos\beta\cos\omega$$

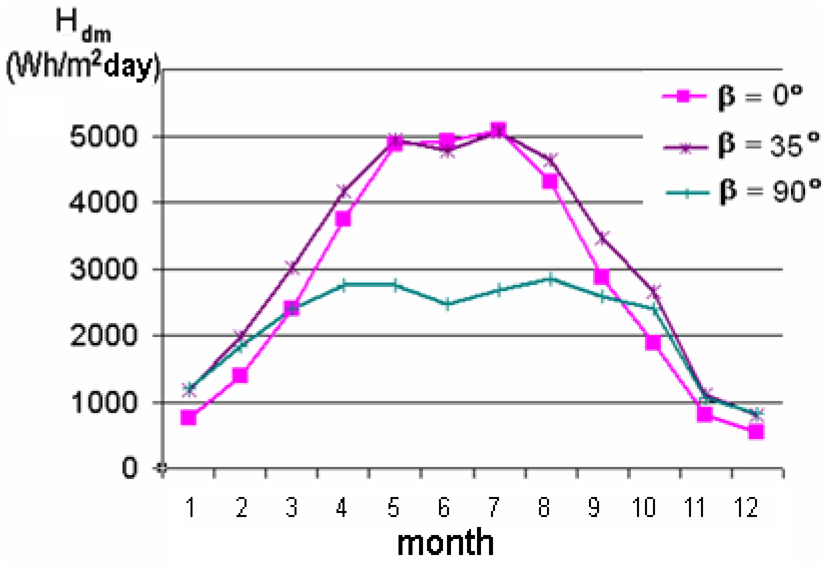
$$+ [\mathrm{sign}(\phi)]\cos\delta\sin\phi\sin\beta\cos\alpha\cos\omega + \cos\delta\sin\alpha\sin\omega\sin\beta$$

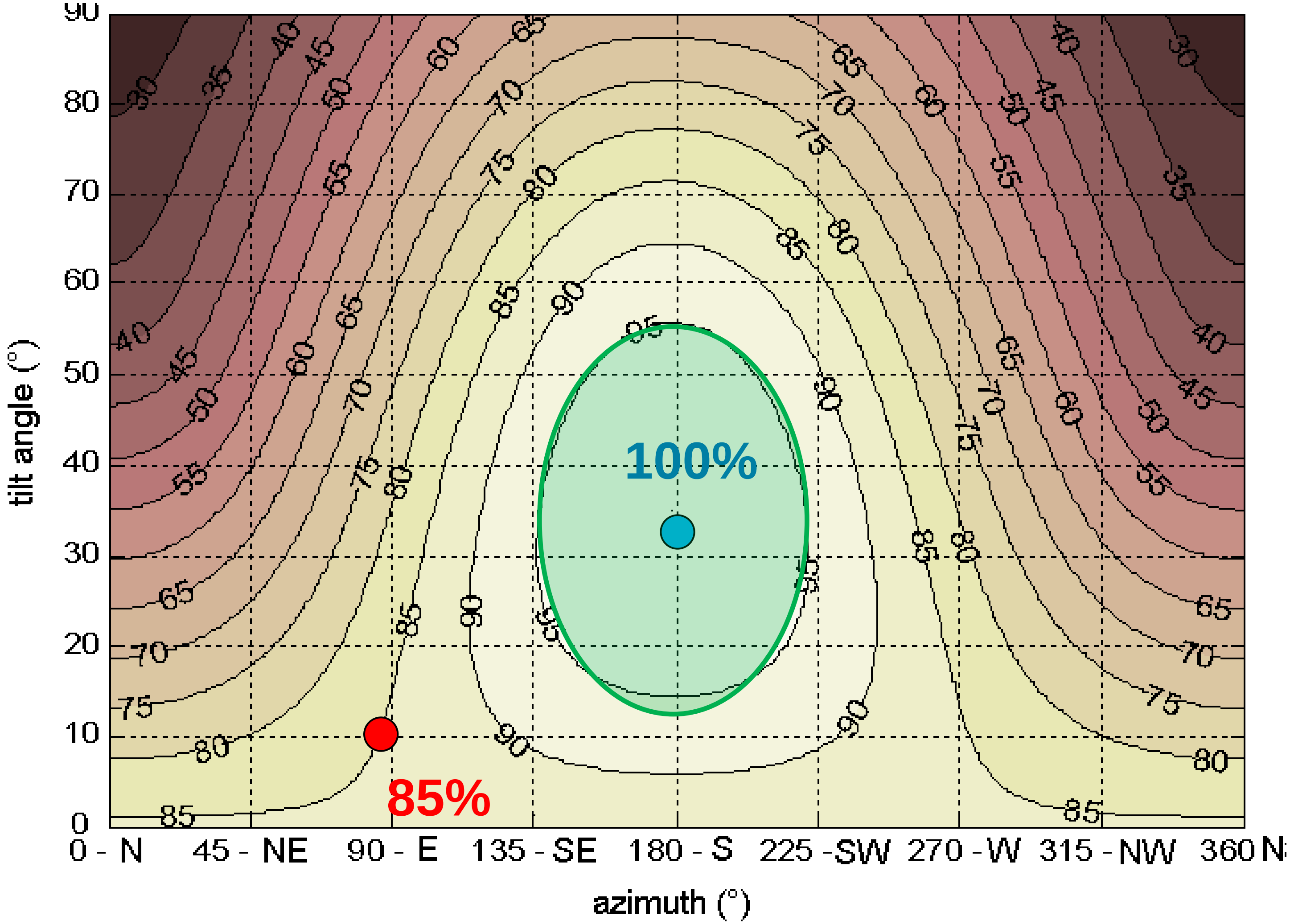
$$\cos\theta_S = [\mathrm{sign}(\phi)]\sin\delta\sin(abs(\phi) - \beta) + \cos\delta\cos(abs(\phi) - \beta)\cos\omega$$

Clear sky



Reality:





http://sunbird.jrc.it/pvgis/apps/pvest.php

1. Light absorption in materials and excess carrier generation

Absorption is due to interactions with material particles (electrons and nucleus).
If particle energy before interaction was W_1, after photon absorption is $W_1 + h\nu$

- **interactions with the lattice – low energy photons, results in an increase of temperature**
- **interactions with free electrons - important when the carrier concentration is high, results also in temperature increase**
- **interactions with bonded electrons- the incident light may generate some excess carriers (electron/hole pairs)**