"Solar Energy" WS 2014/2015

Lecture 2: The Sun

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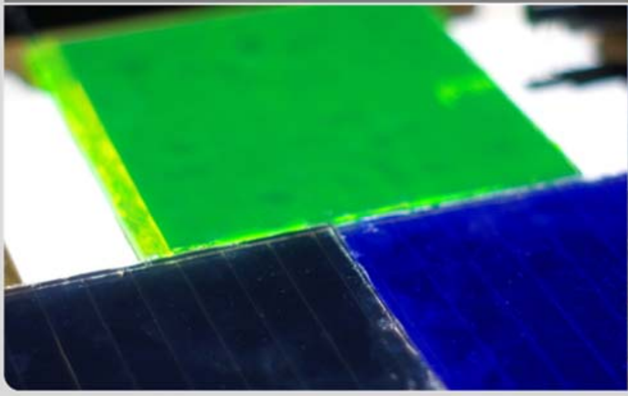
KIT Focus Optics & Photonics



Information

„Solar Energy" lecture (23745) and tutorials (23750)

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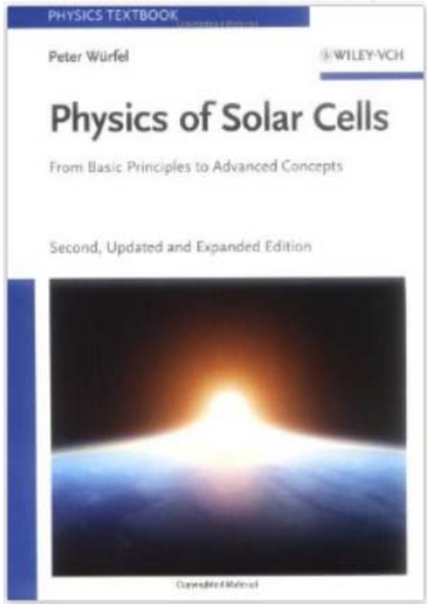
- A bit more about me…

Recommended Reading – Part 2!

- “*Physics of Solar Cells*” by Peter Würfel, Wiley, 2009 (€60 Amazon)

Retired professor from Institute of Applied Physics at KIT!



Units of Radiation

Quantity		Unit		Notes
Name	Symbol	Name	Symbol	
Radiant energy	Q_e	joule	J	energy
Radiant flux	$\Phi_e = dQ/dt$	watt	W *or* J/s	radiant energy per unit time, also called *radiant power*.
Spectral power	$\Phi_{e\lambda}$	watt per metre	$W{\cdot}m^{-1}$	radiant power per wavelength.
Radiant intensity	$I_e = d\Phi_e/d\omega$	watt per steradian	$W{\cdot}sr^{-1}$	power per unit solid angle.
Spectral intensity	$I_{e\lambda}$	watt per steradian per metre	$W{\cdot}sr^{-1}{\cdot}m^{-1}$	radiant intensity per wavelength.
Radiance	$L_e = dI / (dA.\cos \varepsilon)$	watt per steradian per square metre	$W{\cdot}sr^{-1}{\cdot}m^{-2}$	power per unit solid angle per unit *projected* source area. Confusingly also called "intensity" sometimes.
Spectral radiance	$L_{e\lambda}$	watt per steradian per metre^3	$W{\cdot}sr^{-1}{\cdot}m^{-3}$	commonly measured in $W{\cdot}sr^{-1}{\cdot}m^{-2}{\cdot}nm^{-1}$ with surface area and wavelength
Irradiance	$E_e = d\Phi_e/dA_2$	watt per square metre	$W{\cdot}m^{-2}$	power incident on a surface, also called *radiant flux density*. Sometimes wrongly called "intensity"
Spectral irradiance	$E_{e\lambda}$	watt per metre^3	$W{\cdot}m^{-3}$	commonly measured in $W{\cdot}m^{-2}{\cdot}nm^{-1}$, known as solar flux unit.
Radiant emittance	$M_e = d\Phi_e/dA_1$	watt per square metre	$W{\cdot}m^{-2}$	power emitted from a surface.
Spectral radiant emittance	$M_{e\lambda}$	watt per metre^3	$W{\cdot}m^{-3}$	power emitted from a surface per unit wavelength or frequency.
Radiosity	J_e	watt per square metre	$W{\cdot}m^{-2}$	emitted plus reflected power leaving a surface.
Spectral radiosity	$J_{e\lambda}$	watt per metre^3	$W{\cdot}m^{-3}$	emitted plus reflected power leaving a surface per unit wavelength
Radiant exposure	$H_e = \int E\,dt$	joule per square metre	$J{\cdot}m^{-2}$	also referred to as fluence
Radiant energy density	ω_e	joule per metre^3	$J{\cdot}m^{-3}$	

Radiation Physics

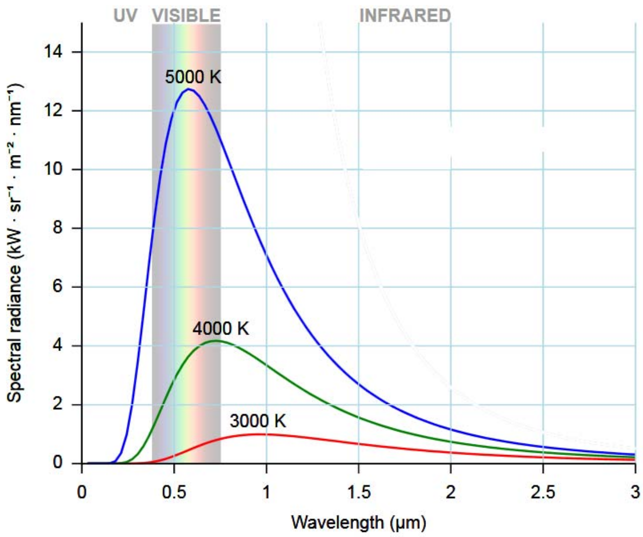
Planck's law describes the electromagnetic radiation emitted by a **black body** that is in thermal equilibrium at a definite temperature.

For a wavelength λ, Planckian radiation can be described as:

$$M_\lambda^0(\lambda,T) = \frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1}$$

where:

- M denotes its spectral radiance
- T its absolute temperature
- k the Boltzmann constant
- h the Planck constant, and
- c the speed of light in the medium



Source: http://en.wikipedia.org/wiki/Black_body

Radiation Physics

Cooling of a body due to thermal radiation is often approximated using a "grey body" with an emissivity $\varepsilon \leq 1$ and the spectral radiance becomes:

$$M_\lambda^0(\lambda,T) = \varepsilon(\lambda)\frac{2\pi hc^2}{\lambda^5} \cdot \frac{1}{\exp\left(\frac{hc}{\lambda kT}\right) - 1}$$

Also, Kirchhoff's law of thermal radiation tells us that for an arbitrary body emitting and absorbing thermal radiation in thermodynamic equilibrium, the emissivity is equal to the absorptivity.

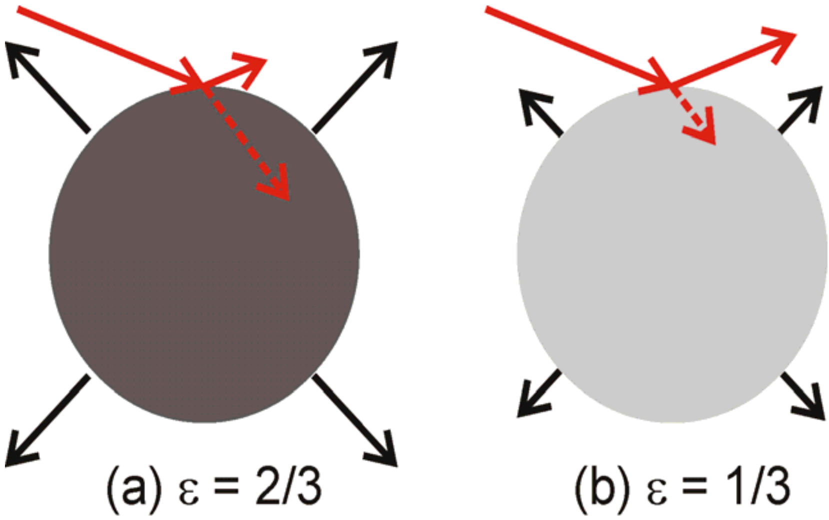
$$\varepsilon(\lambda) = \alpha(\lambda)$$

Thus:

- a good absorber is a good emitter,
- a poor absorber is a poor emitter,
- and therefore a good reflector must be a poor absorber.
  (e.g. lightweight emergency thermal blankets are based on reflective metallic coatings, which lose little heat by radiation)

Radiation Physics

Kirchoff's law of thermal radiation: **(a)** a body that absorbs well also emits well while for **(b)** the opposite is true



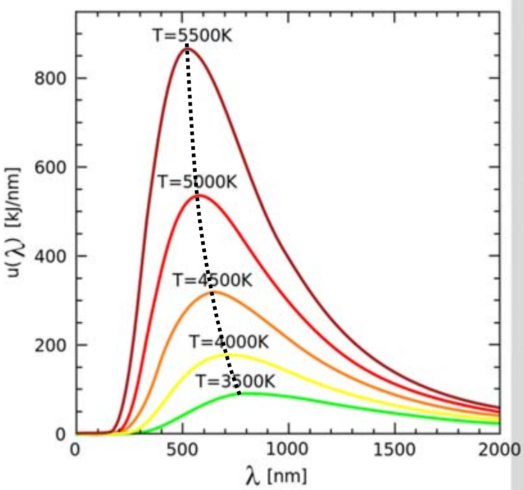
Source: *http://en.wikipedia.org/wiki/Black_body*

Radiation Physics

Further, Wien's displacement law states that the wavelength distribution of thermal radiation from a black body at any temperature has essentially the same shape as the distribution at any other temperature, except that each wavelength is displaced on the graph.

Thus, there's an inverse relationship between the wavelength of the emission peak of a black body and its temperature when expressed as a function of wavelength:

$$\lambda_{max} T = b$$
$$= 2897.8 \ \mu m \ K$$



Source: Adapted from http://en.wikipedia.org/wiki/Wien's_displacement_law

Radiation Physics

The integration of Planck's law over all wavelengths provides the total energy per unit of time per unit of surface area radiated by a black-body maintained at a temperature $T \equiv$ Stefan–Boltzmann law:

$$M^0(T) = \int_{\lambda=0}^{\infty} M_\lambda^0 \, d\lambda = \sigma T^4$$

where σ is the Stefan–Boltzmann constant, $\sigma \approx 5.67 \times 10^{-8}$ W/(m^{2}K^4)

To remain in thermal equilibrium at constant temperature T, the black body must absorb or internally generate this amount of power P over the given area A

$$P = M^0(T) \cdot A$$
$$= A \, \sigma T^4$$

Solar Radiation

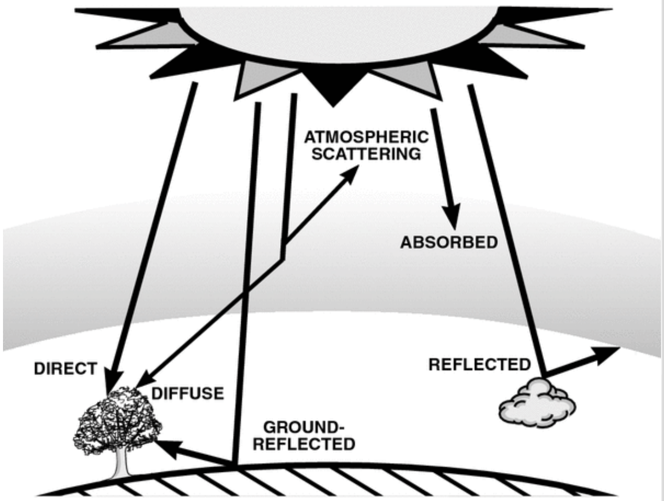
Solar radiation undergoes a series of events on its way to planet Earth:

Scattering – due to particles in the atmosphere

Absorption – due to gases in the atmosphere

Reflection – from molecules, water droplets, ice crystals in high cloud, aerosols, etc. The fraction of this sunlight that reaches Earth is called **diffuse** solar radiation.

Global solar radiation is the sum of the **direct** plus the diffuse solar radiation



Source: http://www.newport.com/Introduction-to-Solar-Radiation/411919/1033/content.aspx

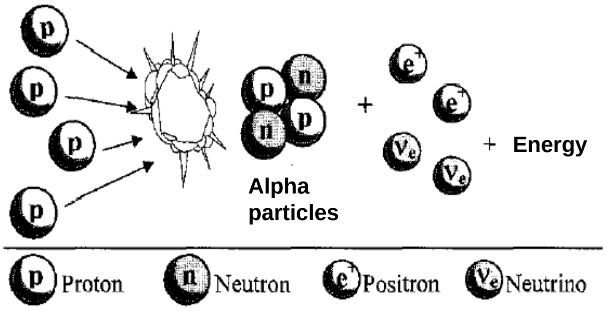
Solar Radiation

Table 2.2 *Data for the Sun and the Earth*

	Sun	*Earth*	*Ratio*
Diameter (km)	1,392,520	12,756	1:109
Circumference (km)	4,373,097	40,075	1:109
Surface (km^2)	$6.0874 \cdot 10^{12}$	$5.101 \cdot 10^{8}$	1:11,934
Volume (km^3)	$1.4123 \cdot 10^{18}$	$1.0833 \cdot 10^{12}$	1:1,303,670
Mass (kg)	$1.9891 \cdot 10^{30}$	$5.9742 \cdot 10^{24}$	1:332,946
Average density (g/cm^3)	1.409	5.516	1:0.26
Gravity (surface) (m/s^2)	274.0	9.81	1:28
Surface temperature (K)	5777	288	1:367
Centre temperature (K)	15,000,000	6700	1:2200

Solar Radiation

$$4\,^1_1\text{p} \rightarrow {}^4_2\alpha + 2e^+ + 2\nu_e + \Delta E$$



$$E = m \cdot c^2$$

$$\Delta m = 4.3 \cdot 10^9 \text{ kg/s}$$

$$\Delta E = 3.85 \cdot 10^{26} \text{ J/s}$$

$$\Phi_S = \frac{dE_S}{dt} = \frac{dM_S}{dt} \cdot c^2$$

$$= 3.85 \cdot 10^{26} W$$

Nuclear reaction: particles colliding result in generation of energy, exhibited as solar radiation

$$\frac{\Phi_S}{A_S} = 63.11 \frac{\text{MW}}{\text{m}^2}$$ Radiant flux of the Sun with surface area $A_S \equiv$ irradiance

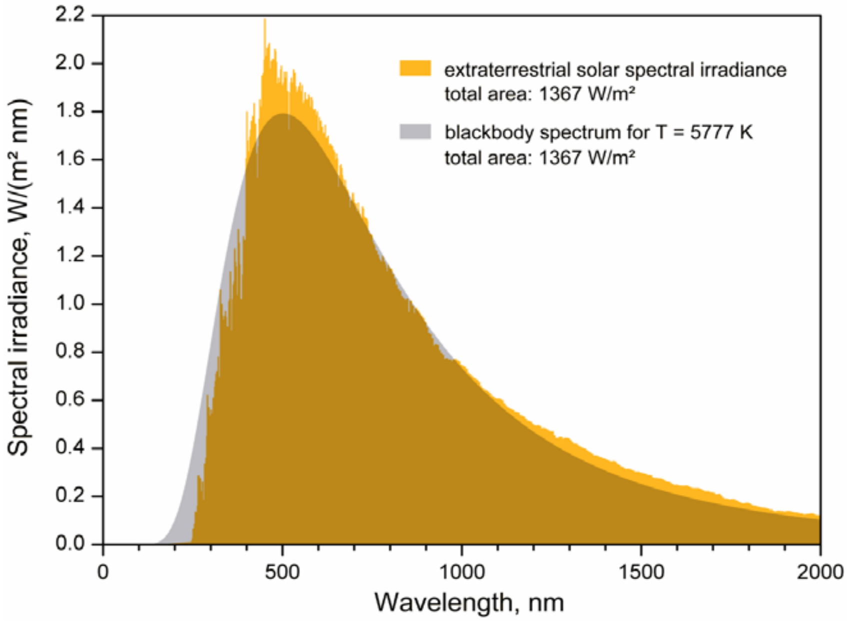
$$\frac{\Phi_S}{A_S} = \sigma_B \cdot T^4 \Rightarrow \boxed{T = 5777K}$$

Remember S-B Law for Sun as a black body, can now calculate surface temperature of the Sun

Solar Radiation

Extraterrestrial solar spectrum:

- Continuous spectrum
- Peak at about 478nm
- Sometimes 5900 K or 6000 K used instead



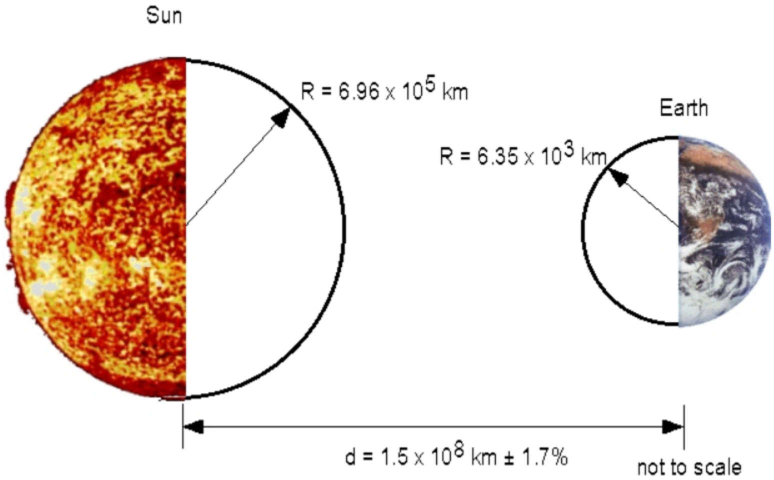
Source: http://en.wikipedia.org/wiki/Effective_temperature

Solar Radiation

By integrating the irradiance of the extraterrestrial Sun over the entire Wavelength range one obtains the **extraterrestrial solar constant:**

$$E_0 = 1367 \pm 7 \;\; W/m^2$$

$$E_0 = \frac{\Phi_S}{4\pi d^2}$$



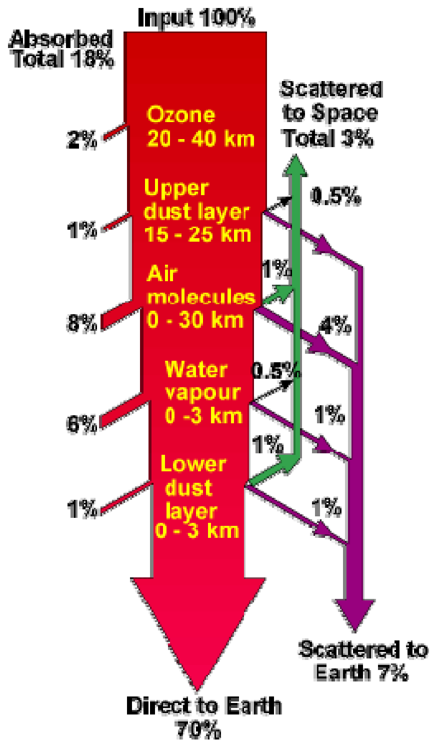
This is the average irradiance outside the Earth´s atmosphere on a plane that is perpendicular to the solar radiation at an average distance *d* between Earth and Sun

Source: http://www.pveducation.org/pvcdrom/properties-of-sunlight/solar-radiation-outside-earths-atmosphere

Solar Radiation

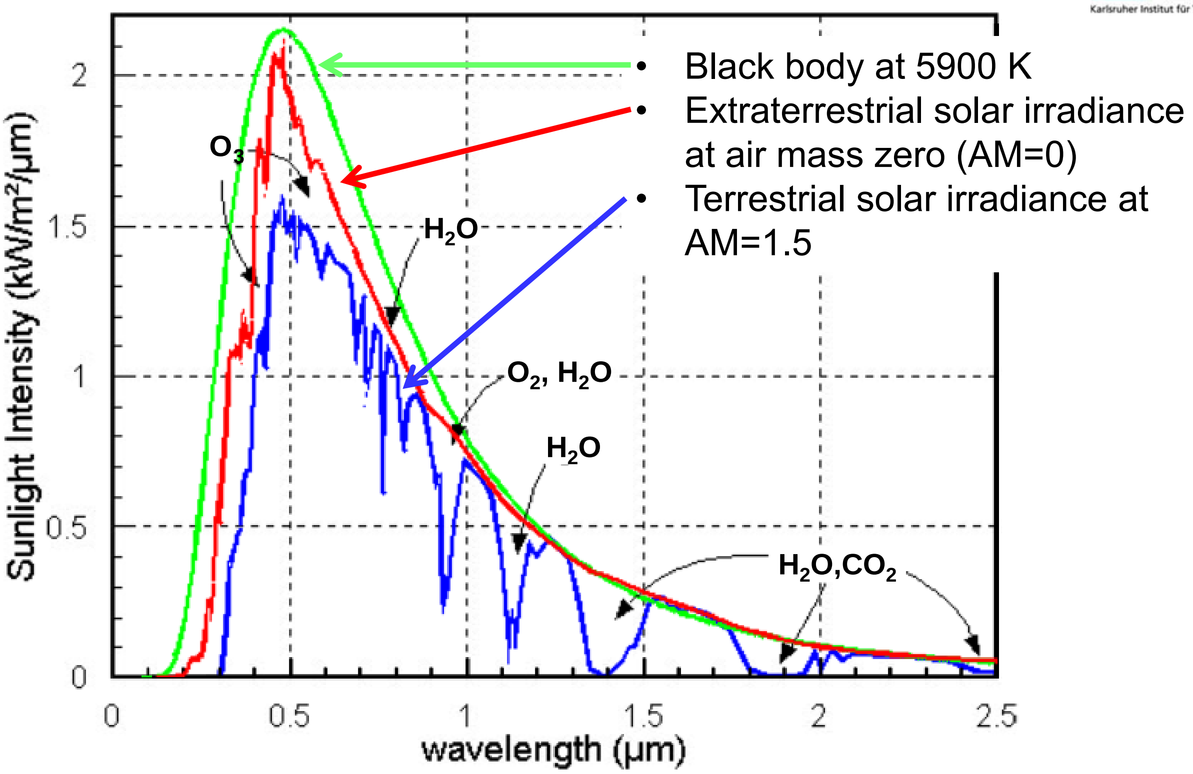
While the solar radiation incident on the Earth's atmosphere is relatively constant, the radiation at the Earth's surface varies widely due to:

- 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



Source: Hu C, White RM. Solar Cells: From Basic to Advanced Systems. New York: McGraw-Hill; 1983.

Solar Radiation



Source: http://www.pveducation.org/pvcdrom/properties-of-sunlight/atmospheric-effects

Solar Radiation

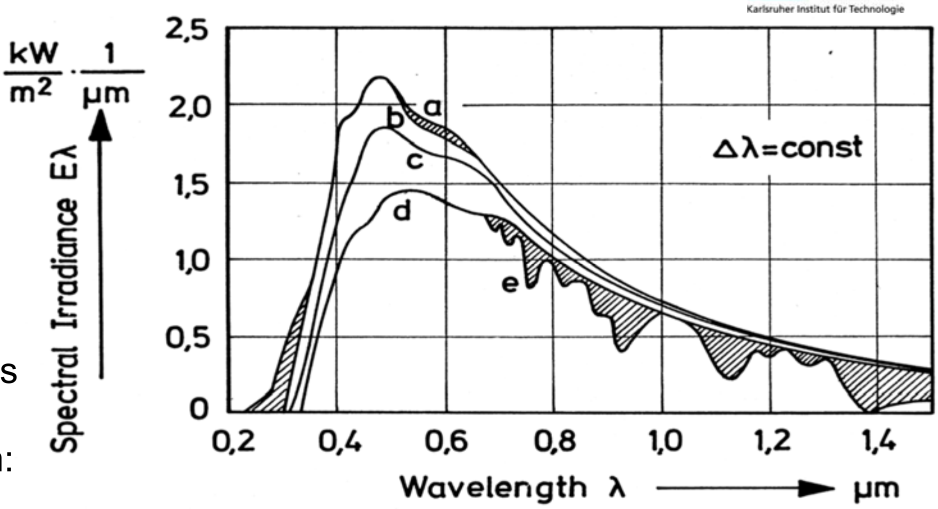
The intensity of solar irradiance is reduced as it passes through the Earth's atmosphere due to **absorption** and **scattering**:

- The **ozone layer** (O_3) in the stratosphere filters rays of light with a wavelength of less than 300nm out.
- **Trace gases** (H_2O, O_2, CO_2 shown - others incl. N_2O, CH_4, hydrochlorofluorocarbons and aerosols (e.g. containing S) in the troposphere **absorb** infrared light
- **Rayleigh scattering** from specks of dust or nitrogen and oxygen molecules with diameter < λ of the light, proportional to λ^{-4}

  $\rightarrow$ blue light is scattered more strongly than red
- **Mie scattering** from dust, aerosols and molecules with a diameter > λ of the light. Not strongly wavelength dependent, e.g. results in the white light from mist or fog

Solar Radiation

Effect of different absorption and scattering processes on the shape of the irradiance spectrum:



a) extraterrestrial solar irradiance
b) after absorption by ozone
c) after Rayleigh scattering
d) after absorption and scattering due to aerosols
e) after absorption due to water vapour and oxygen
$\Rightarrow$ direct solar irradiance striking planet Earth

Solar Radiation on Inclined Surfaces

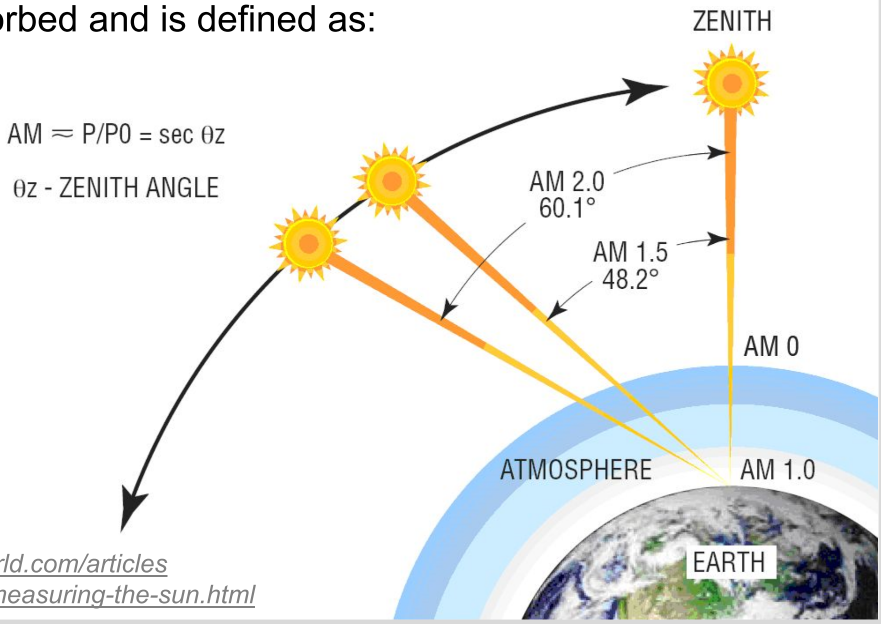
Air Mass (AM) ≡ pathlength light takes through the atmosphere normalized to the shortest possible path length (sun directly overhead).

AM quantifies the reduced power of sunlight as it passes through the atmosphere and is absorbed and is defined as:

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

where θ is the angle from the vertical (zenith angle)

Thus, when sun is directly overhead AM=1



Source: http://www.laserfocusworld.com/articles/2009/05/photovoltaics-measuring-the-sun.html

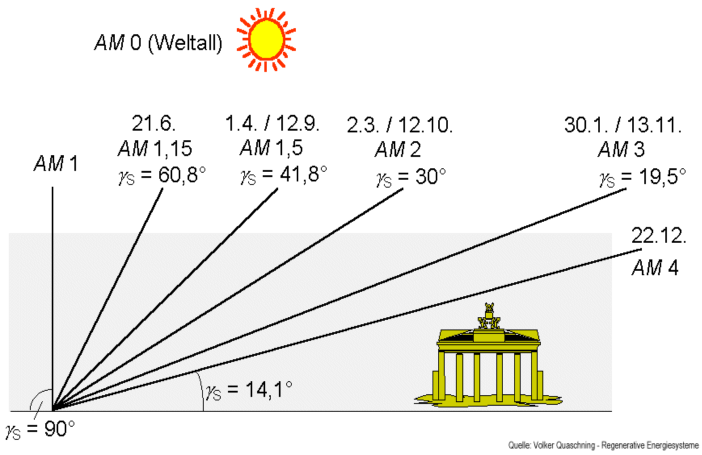
Solar Radiation on Inclined Surfaces

Alternate definition (e.g. as used in Solarenergie course):

$$AM = \frac{1}{\sin(\gamma_S)}$$

where γ_S is the angle from the **horizontal**

e.g. AM values for different days in Berlin (at midday)



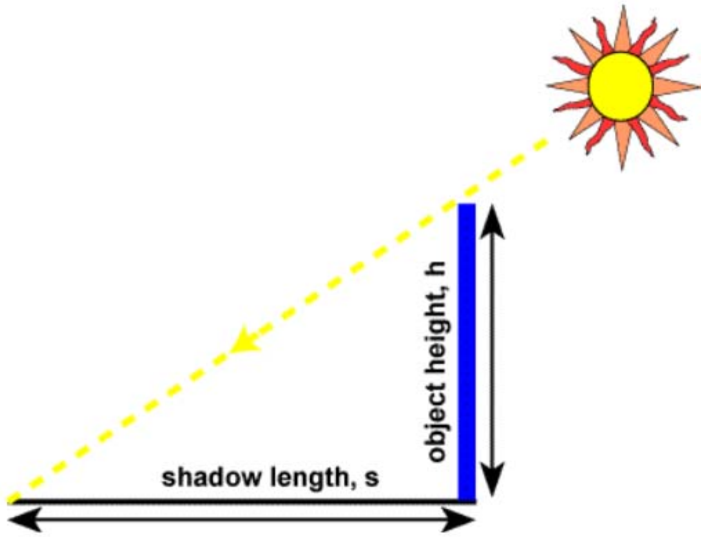
Solar Radiation on Inclined Surfaces

An easy method to estimating* the AM is from the shadow of a vertical pole:

$$AM = \sqrt{1 + \left(\frac{s}{h}\right)^2}$$

where:
s = shadow length
h = object height

* assumption that atmosphere is a flat horizontal layer

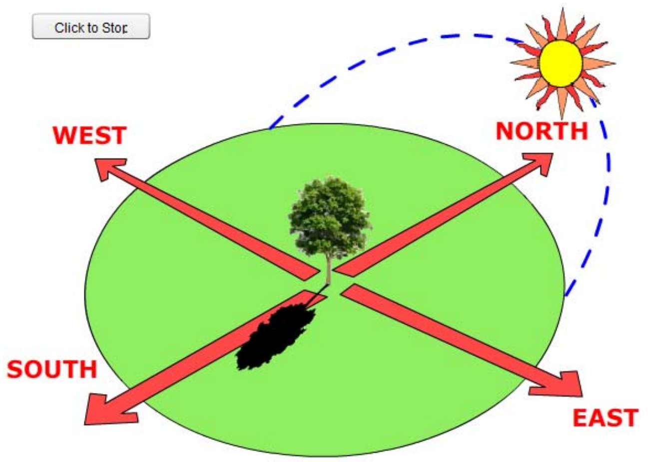


Source: http://www.pveducation.org/pvcdrom/properties-of-sunlight/air-mass

Solar Radiation on Inclined Surfaces

The apparent motion of sun, caused by the rotation of the Earth about its axis, changes angle at which direct sunlight strikes Earth.

From a fixed location on Earth, the sun appears to move across the sky. It's position depends on the location of a point on Earth, the time of day and the time of year

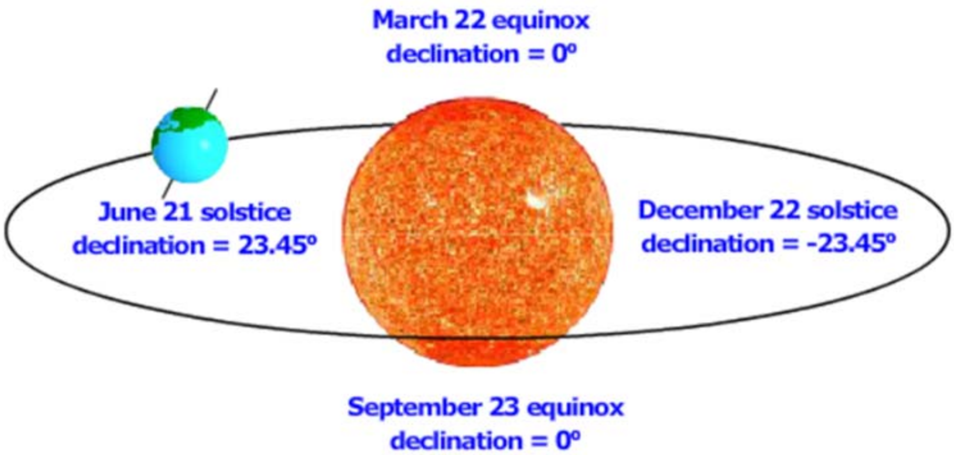


Source: http://www.pveducation.org/pvcdrom/properties-of-sunlight/motion-of-sun

Solar Radiation on Inclined Surfaces

The declination angle (δ) varies seasonally due to the tilt of the Earth on its axis of rotation and the rotation of the Earth around the sun

Earth is tilted by 23.45° and the declination angle varies plus or minus this amount. Only at the spring and fall equinoxes is the $\delta = 0°$



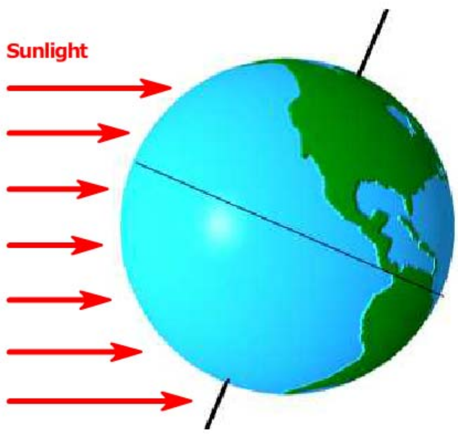
Source: http://www.pveducation.org/pvcdrom/properties-of-sunlight/declination-angle

Solar Radiation on Inclined Surfaces

The declination angle can be calculated using:

$$AM = \sin^{-1}\left(\sin(23.45°)\sin\left(\frac{360}{365}(d-81)\right)\right)$$

where d is the day of the year with Jan 1 as $d = 1$



Source: http://www.pveducation.org/pvcdrom/properties-of-sunlight/declination-angle

Solar Radiation on Inclined Surfaces

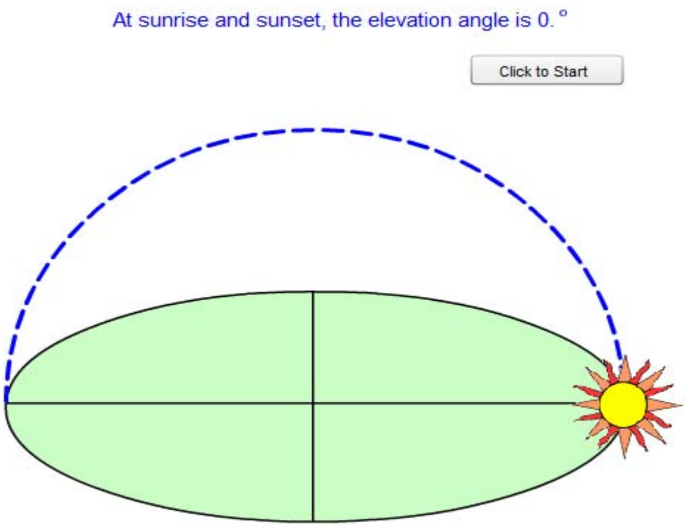
The elevation angle or altitude angle $\alpha \equiv$ angular height of Sun in the sky measured from the horizontal

The elevation angle is 0° at sunrise and 90° when the sun is directly overhead (e.g. which occurs at equator on the spring and autumn equinoxes).

The elevation angle varies throughout day and year

N.B. related to zenith angle ζ via:

$$\zeta = 90^\circ - \alpha$$



Source: http://www.pveducation.org/pvcdrom/properties-of-sunlight/elevation-angle

Solar Radiation on Inclined Surfaces

Maximum elevation angle: important parameter for design of PV systems

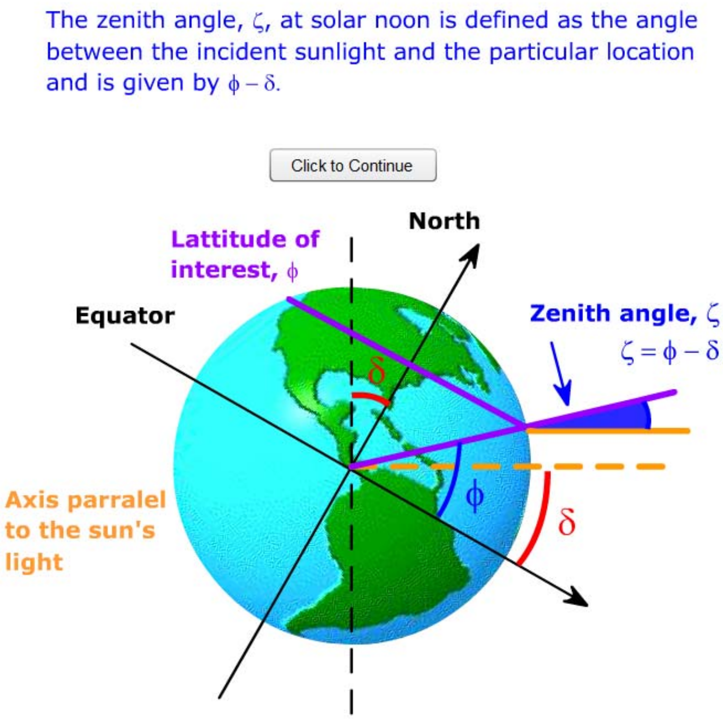
Occurs at solar noon and depends on both latitude and declination angle – in Northern Hemisphere:

$$\alpha = 90^\circ - \varphi + \delta$$

where φ = latitude angle and δ = declination angle

Southern Hemisphere:

$$\alpha = 90^\circ + \varphi - \delta$$



Solar Radiation on Inclined Surfaces

Karlsruhe: latitude 49°N

Winter solstice on 21st Dec

$$\alpha = 90^\circ - 49^\circ - 23.5^\circ$$
$$= 17.5^\circ$$

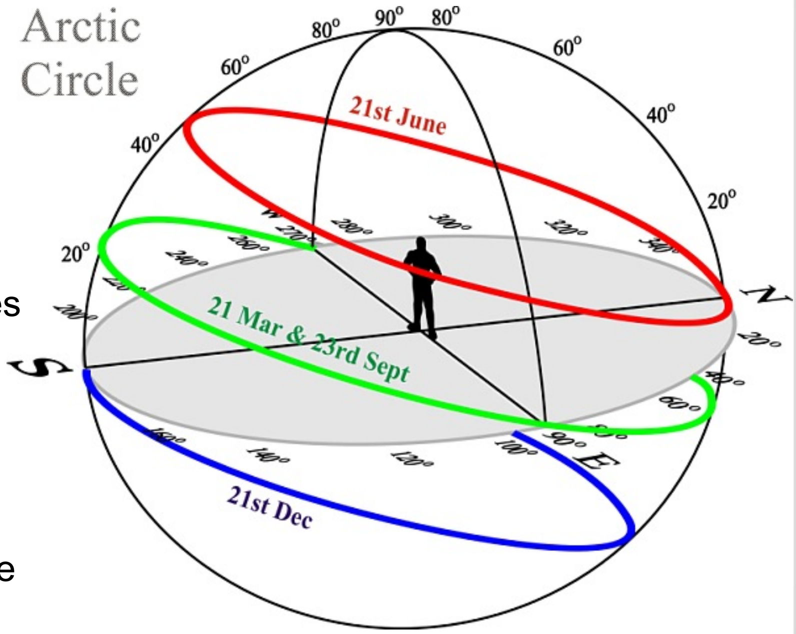
Spring and autumn equinoxes (21st Mar & 21st Sep)

$$\alpha = 90^\circ - 49^\circ + 0^\circ$$
$$= 41^\circ$$

Summer solstice on 21st June

$$\alpha = 90^\circ - 49^\circ + 23.5^\circ$$
$$= 64.5^\circ$$

Arctic Circle



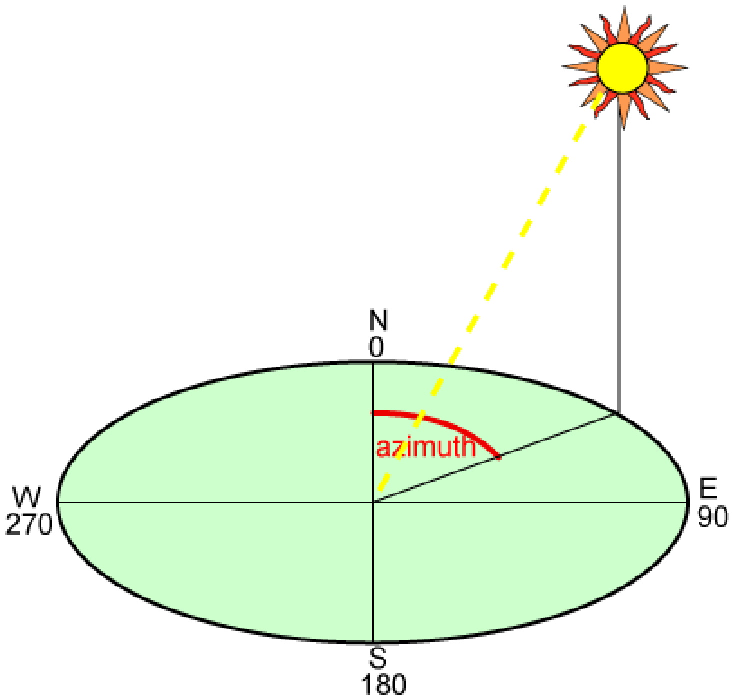
…and at the Arctic Circle….

Source: http://www.hsphys.com/dayinb.jpg

Solar Radiation on Inclined Surfaces

Azimuth angle is the compass direction from which the sunlight is coming

At solar noon, the sun is always directly south in northern hemisphere and directly north in the southern hemisphere



Source: http://www.pveducation.org/pvcdrom/properties-of-sunlight/azimuth-angle

Solar Radiation on Inclined Surfaces

Effective reduction in solar irradiance as a function of elevation angle.

Mie scattering varies greatly due to local environmental conditions (e.g. smog)

Further reductions due to heavy cloud, rain or snow, etc not considered

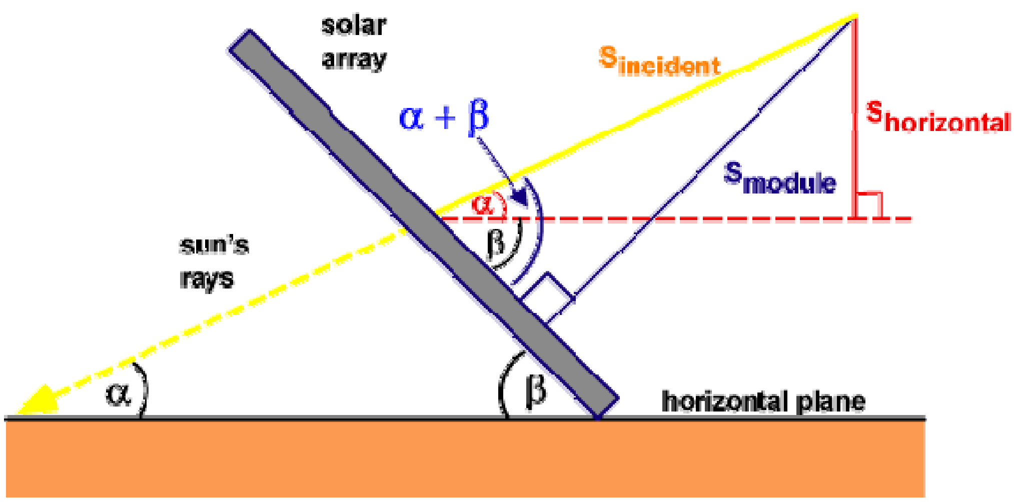
γ_S	AM	Absorption	Rayleigh-Streuung	Mie-Streuung	Gesamt-schwächung
90°	1,00	8,7 %	9,4 %	0 ... 25,6 %	17,3 ... 38,5 %
60°	1,15	9,2 %	10,5 %	0,7 ... 29,5 %	19,4 ... 42,8 %
30°	2,00	11,2 %	16,3 %	4,1 ... 44,9 %	28,8 ... 59,1 %
10°	5,76	16,2 %	31,9 %	15,4 ... 74,3 %	51,8 ... 85,4 %
5°	11,5	19,5 %	42,5 %	24,6 ... 86,5 %	65,1 ... 93,8 %

N.B. defined using γ_S

Solar Radiation on Inclined Surfaces

The power incident on a PV module
$\propto$ power contained in the sunlight + angle between the module and the sun

When PV module and sunlight are perpendicular the power density is at its maximum, but the angle between the sun and a fixed surface is continually changing and needs to be calculated as follows:



Source: http://www.pveducation.org/pvcdrom/properties-of-sunlight/solar-radiation-on-tilted-surface

Solar Radiation on Inclined Surfaces

The irradiance (here labelled *S* instead of *E*) on a PV module:

$$S_{horizontal} = S_{incident} \sin\alpha$$

$$S_{module} = S_{incident} \sin(\alpha + \beta)$$

Remember that values for α, δ, φ etc were determined previously so now only need to know β (tilt angle of solar panel)

$$S_{module} = \frac{S_{horizontal} \sin(\alpha + \beta)}{\sin\alpha}$$

Solar Radiation on Inclined Surfaces

When considering the azimuth angle the situation gets more complex….
(also only considering direct radiation)

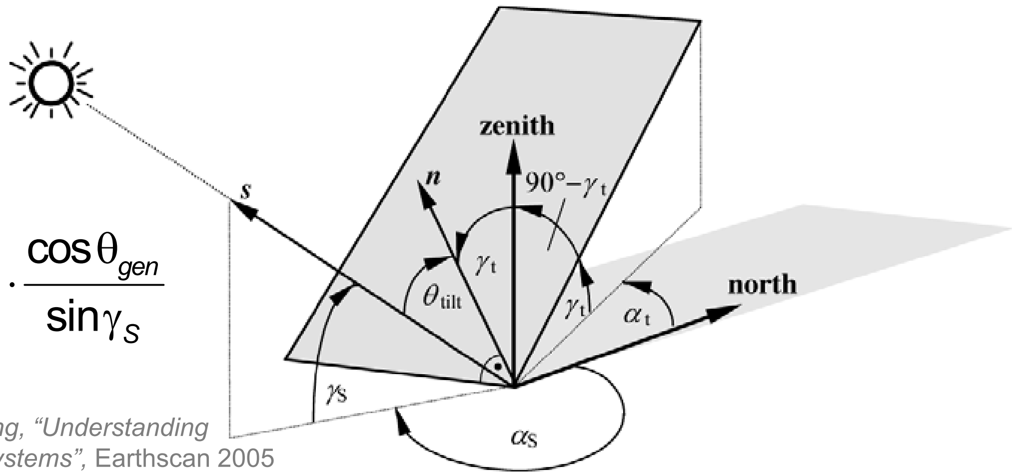
$$\theta_{tilt} = \arccos(s \cdot n) =$$

$$= \arccos(-\cos\alpha_S \cdot \cos\gamma_S \cdot \cos\alpha_t \cdot \sin\gamma_t -$$

$$\sin\alpha_S \cdot \cos\gamma_S \cdot \sin\alpha_t \cdot \sin\gamma_t + \sin\gamma_S \cdot \cos\gamma_t)$$

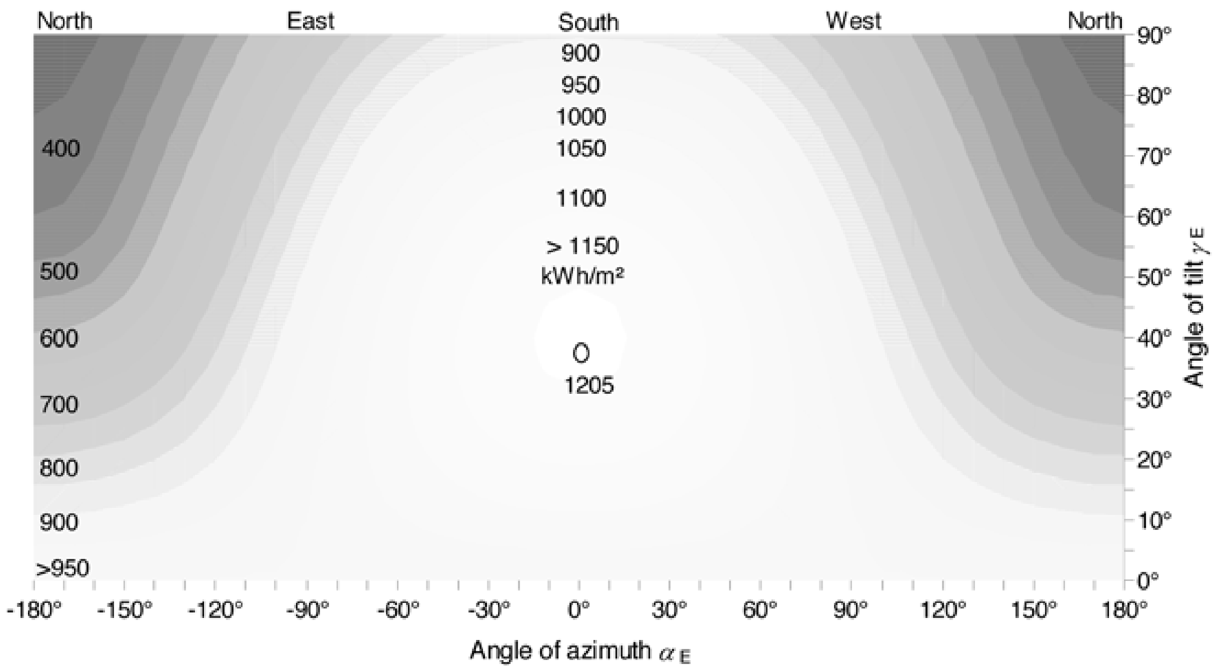
$$= \arccos) - \cos\gamma_S \cdot \sin\gamma_t \cdot \cos(\alpha_S - \alpha_t) + \sin\gamma_S \cdot \cos\gamma_t)$$

$$E_{tilt} = E_{horizontal} \cdot \frac{\cos\theta_{gen}}{\sin\gamma_S}$$



Source: V. Quaschning, "Understanding Renewable Energy Systems", Earthscan 2005

Solar Radiation on Inclined Surfaces

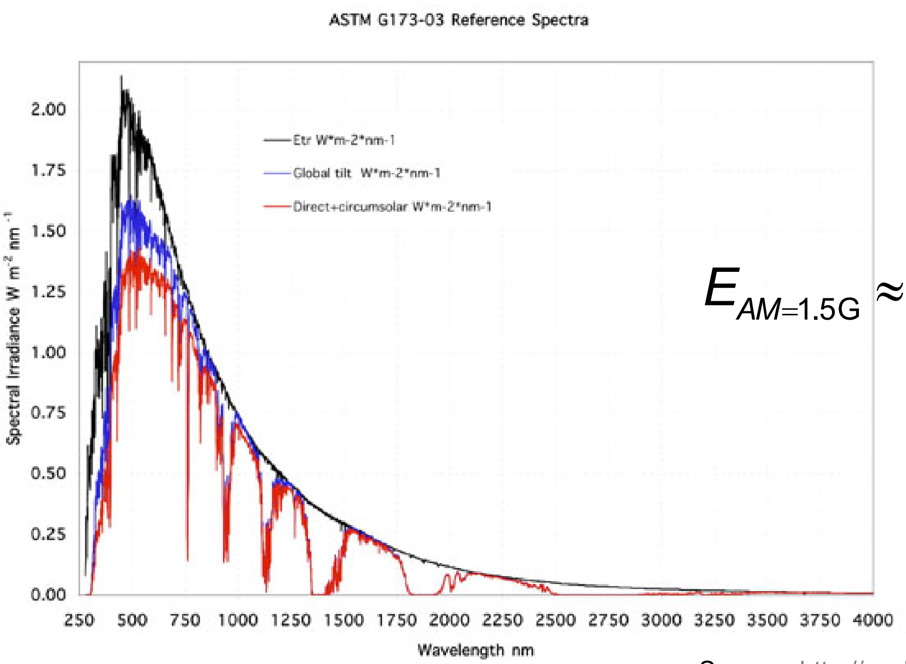


E.g. for Berlin (52.5°N) – note broad tolerance to "wrong" orientation

Source: V. Quaschning, "Understanding Renewable Energy Systems", Earthscan 2005

Solar Radiation on Inclined Surfaces

"Standard" solar spectrum is taken to be **AM1.5 global** irradiance incident on an inclined plane at 37° tilt toward the equator and facing the sun



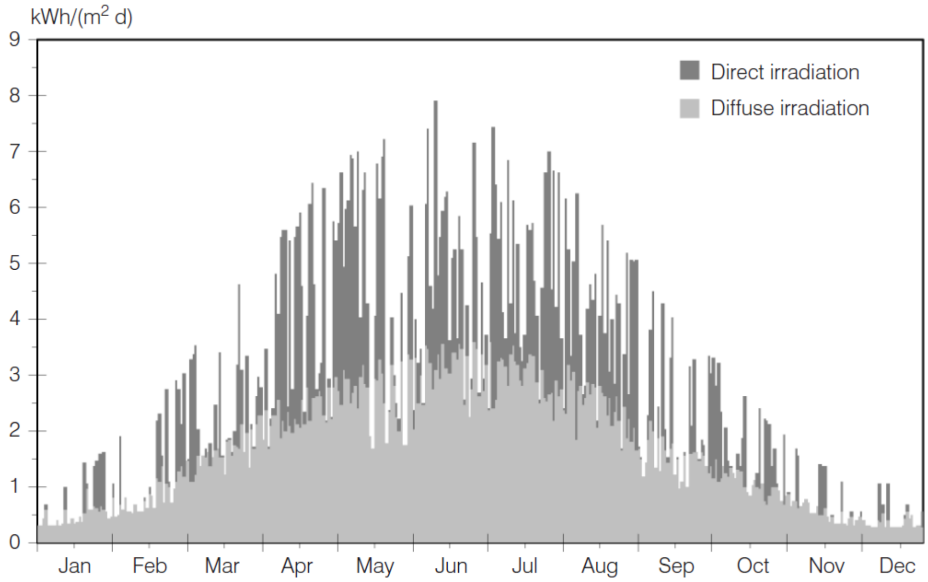
$$E_{AM=1.5G} \approx 1.0\text{kW/m}^2$$

Source: http://rredc.nrel.gov/solar/spectra/am1.5/

Global, Direct & Diffuse Irradiance

Earlier we saw a figure for diffuse radiation of 10%, but actually a huge amount of variability exists

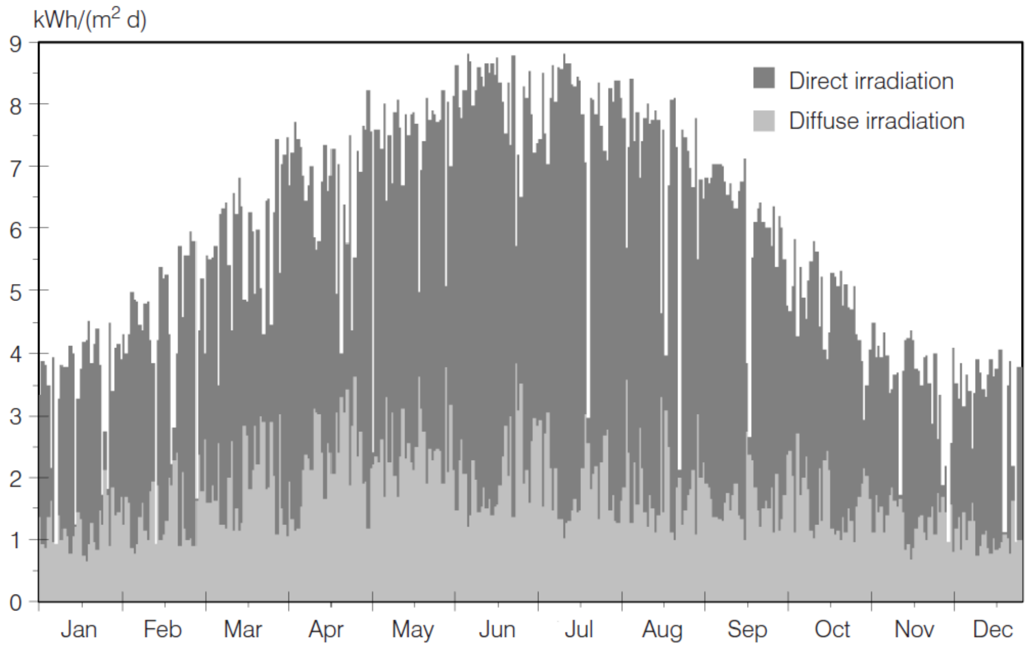
e.g. in central/northern Europe it is closer to 60% (shown for Berlin)



Source: V. Quaschning, "Understanding Renewable Energy Systems", Earthscan 2005

Global, Direct & Diffuse Irradiance

Contrast to Cairo…



Source: V. Quaschning, "Understanding Renewable Energy Systems", Earthscan 2005

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Table 2.6 *Monthly Average Daily Direct and Diffuse Irradiation in kWh/(m² day) in Berlin and Cairo*

		Jan	*Feb*	*Mar*	*Apr*	*May*	*June*	*July*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Average*
Berlin	Direct	0.17	0.40	1.03	1.42	2.13	2.58	2.29	2.05	1.38	0.54	0.22	0.10	1.20
	Diffuse	0.44	0.74	1.41	2.07	2.64	2.86	2.97	2.53	1.67	1.05	0.54	0.35	1.61
Cairo	Direct	1.74	2.37	3.07	3.78	4.56	5.16	4.93	4.57	3.86	3.07	1.96	1.58	3.39
	Diffuse	1.35	1.63	2.08	2.49	2.47	2.40	2.41	2.19	2.01	1.62	1.49	1.28	1.95

Table 2.7 *Annual Average Daily Direct and Diffuse Irradiation in kWh/(m²* day)

	Bergen	*Berlin*	*London*	*Rome*	*LA*	*Cairo*	*Bombay*	*Upington*	*Sydney*
Direct	0.86	1.20	0.99	2.41	3.03	3.39	2.75	4.70	2.42
Diffuse	1.29	1.61	1.47	1.78	2.07	1.95	2.39	1.47	2.13

Source: V. Quaschning, "Understanding Renewable Energy Systems", Earthscan 2005

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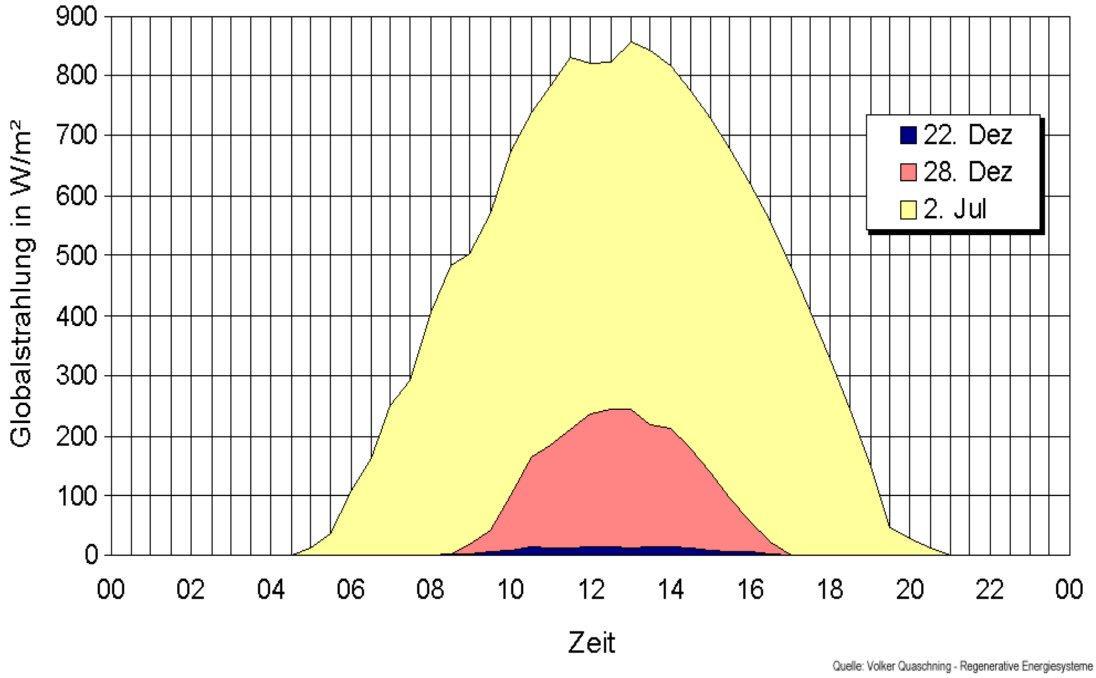
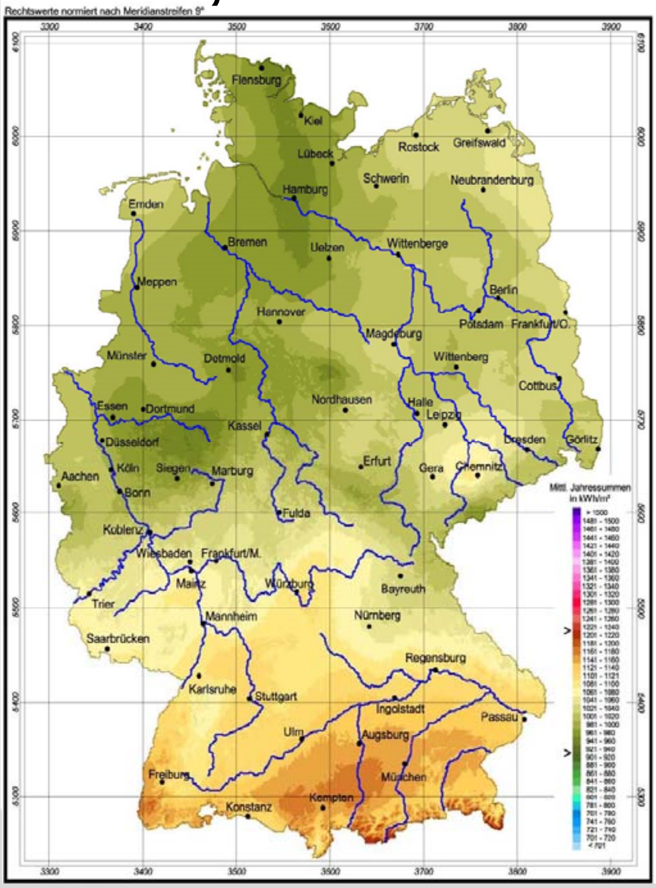
Global irradiance for three days in Karlsruhe in 1991



Source: V. Quaschning, "Understanding Renewable Energy Systems", Earthscan 2005

Global, Direct & Diffuse Irradiance



Peak solar irradiance does not vary greatly

However, the amount of solar energy incident upon a flat plate does vary notably with location (more in south, less in north)

Germany: annual average 1000 kWh/m^2
≈1000 sunshine-hours per year (at 1 kW/m^2) with a yearly averge of 115 W/m^2

c.f. Saudi-Arabia: 2500 kWh/m^2 per annum, average irradiance 285 W/m^2

Global, Direct & Diffuse Irradiance

Daily averages for global solar irradiation (kWh/(m^2.day)) incident on a horizontal surface for different cities in Germany

	Jan	Feb	Mrz	Apr	Mai	Jun	Jul	Aug	Sep	Okt	Nov	Dez	kWh m2/a
Berlin	0,54	1,14	2,47	3,72	4,83	5,56	5,02	4,21	3,16	1,59	0,64	0,39	1015
Hamburg	0,48	1,01	2,13	3,60	4,65	5,29	4,66	3,89	2,82	1,39	0,58	0,33	940
Bremen	0,49	1,07	2,07	3,58	4,64	5,15	4,52	3,87	2,81	1,44	0,62	0,37	934
Hannover	0,51	1,10	2,18	3,62	4,69	5,24	4,59	3,95	2,86	1,49	0,64	0,38	953
Göttingen	0,56	1,18	2,32	3,58	4,57	5,09	4,49	3,80	2,84	1,55	0,68	0,43	947
Braunlage	0,58	1,22	2,34	3,62	4,55	5,15	4,56	3,79	2,90	1,63	0,68	0,45	959
Dortmund	0,53	1,16	2,28	3,73	4,67	4,71	4,33	3,79	2,85	1,53	0,72	0,43	937
Essen	0,56	1,13	2,20	3,52	4,51	4,94	4,36	3,80	2,83	1,59	0,72	0,43	932
Bocholt	0,56	1,15	2,32	4,01	4,93	5,15	4,61	3,90	2,86	1,46	0,72	0,42	978
Münster	0,54	1,17	2,32	3,95	4,96	5,08	4,59	3,86	2,94	1,52	0,70	0,41	978
Osnabrück	0,51	1,10	2,11	3,48	4,54	5,05	4,37	3,75	2,78	1,53	0,66	0,40	923
Köln	0,62	1,26	2,42	3,91	4,73	4,95	4,58	4,10	3,04	1,78	0,79	0,51	996
Aachen	0,63	1,26	2,43	3,92	4,74	4,96	4,59	4,11	3,05	1,79	0,79	0,52	1000
Trier	0,63	1,29	2,47	3,76	4,77	5,08	4,91	4,07	3,04	1,65	0,74	0,49	1004
Lüdenscheid	0,53	1,19	2,37	3,49	4,48	4,45	4,03	3,48	2,76	1,54	0,70	0,43	897
Kahler Asten	0,59	1,25	2,36	3,65	4,72	4,80	4,43	3,68	2,87	1,60	0,69	0,43	947
Frankfurt	0,63	1,29	2,56	3,86	4,92	5,29	5,04	4,26	3,15	1,67	0,72	0,48	1033
Mannheim	0,69	1,37	2,72	4,04	5,11	5,37	5,34	4,48	3,34	1,81	0,78	0,54	1086
Stuttgart	0,75	1,42	2,60	3,78	4,83	5,23	5,37	4,53	3,37	2,03	0,88	0,61	1080
Tübingen	0,78	1,42	2,64	3,86	4,79	5,18	5,36	4,45	3,33	2,02	0,96	0,63	1079
Karlsruhe	0,71	1,36	2,67	3,89	5,05	5,37	5,42	4,55	3,38	1,90	0,81	0,57	1088
Freiburg	1,04	1,75	2,78	4,24	5,06	5,63	5,69	4,67	3,73	2,25	0,12	0,84	1160
München	0,77	1,44	2,60	3,83	4,72	5,27	5,25	4,41	3,48	2,06	0,87	0,57	1076
Kempten	0,91	1,58	2,80	3,79	4,06	4,90	5,13	4,47	3,43	2,19	1,04	0,76	1085
Ulm	0,75	1,40	2,69	3,90	4,88	5,26	5,43	4,54	3,34	1,83	0,80	0,56	1080
Regensburg	0,72	1,37	2,69	2,98	4,92	5,38	5,36	4,43	3,35	1,87	0,78	0,54	1088
Würzburg	0,65	1,33	2,63	3,94	4,99	5,40	5,26	4,37	3,20	1,76	0,76	0,51	1062

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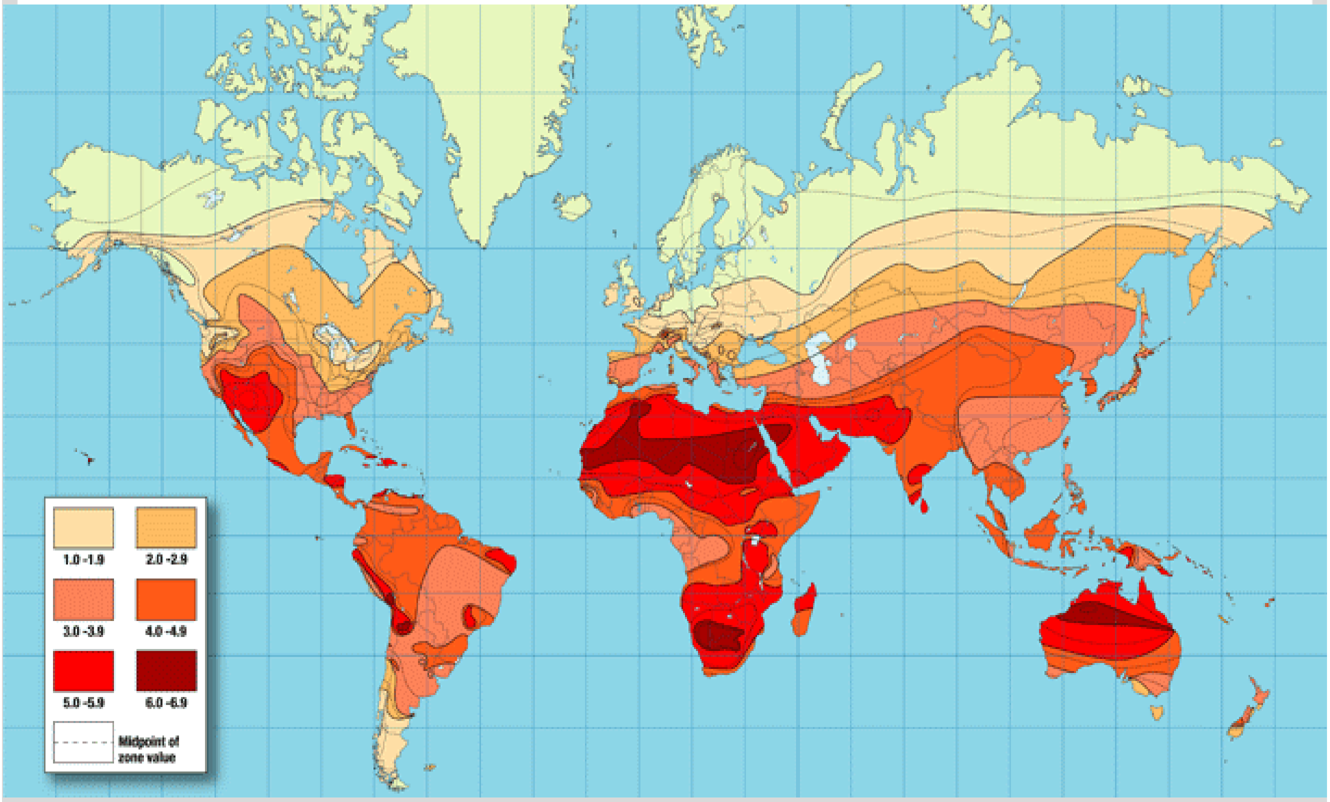
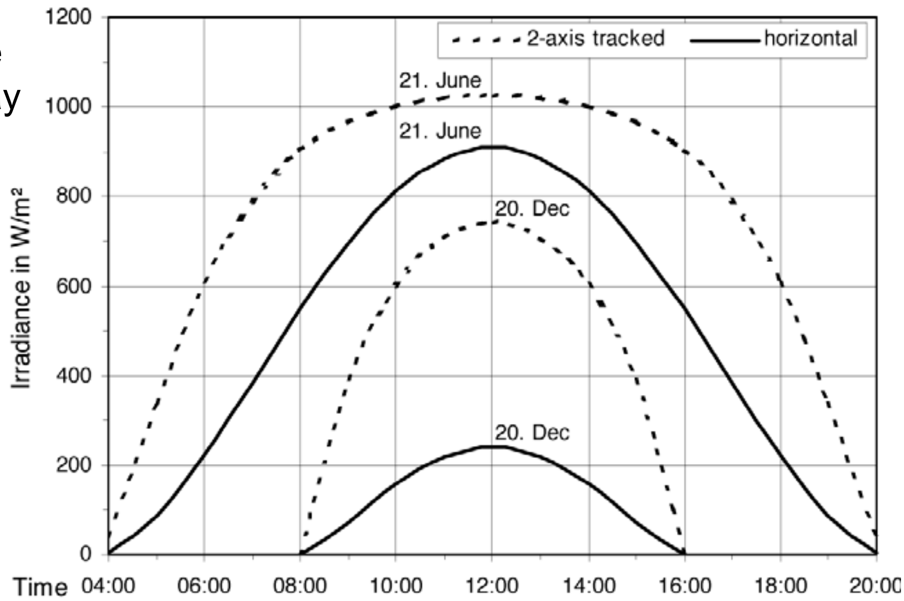


Global, Direct & Diffuse Irradiance

Further gains in the amount of solar radiation that can be harvested can be made by using solar tracking

i.e. the solar panel follows the path of the sun throughout the day

For a 2-axis tracker this results in about 30% more energy whereas for a 1-axis (E-W) tracker it is closer to 20%



Source: V. Quaschning, "Understanding Renewable Energy Systems", Earthscan 2005