Issues for PV:

1) Light is polychromatic

2) The Earth moves (daily, seasonal)

Characteristics of Sunlight

Temperature at the Sun's surface is 6000 K

Solar spectrum approximated as a blackbody (Planck distribution law)

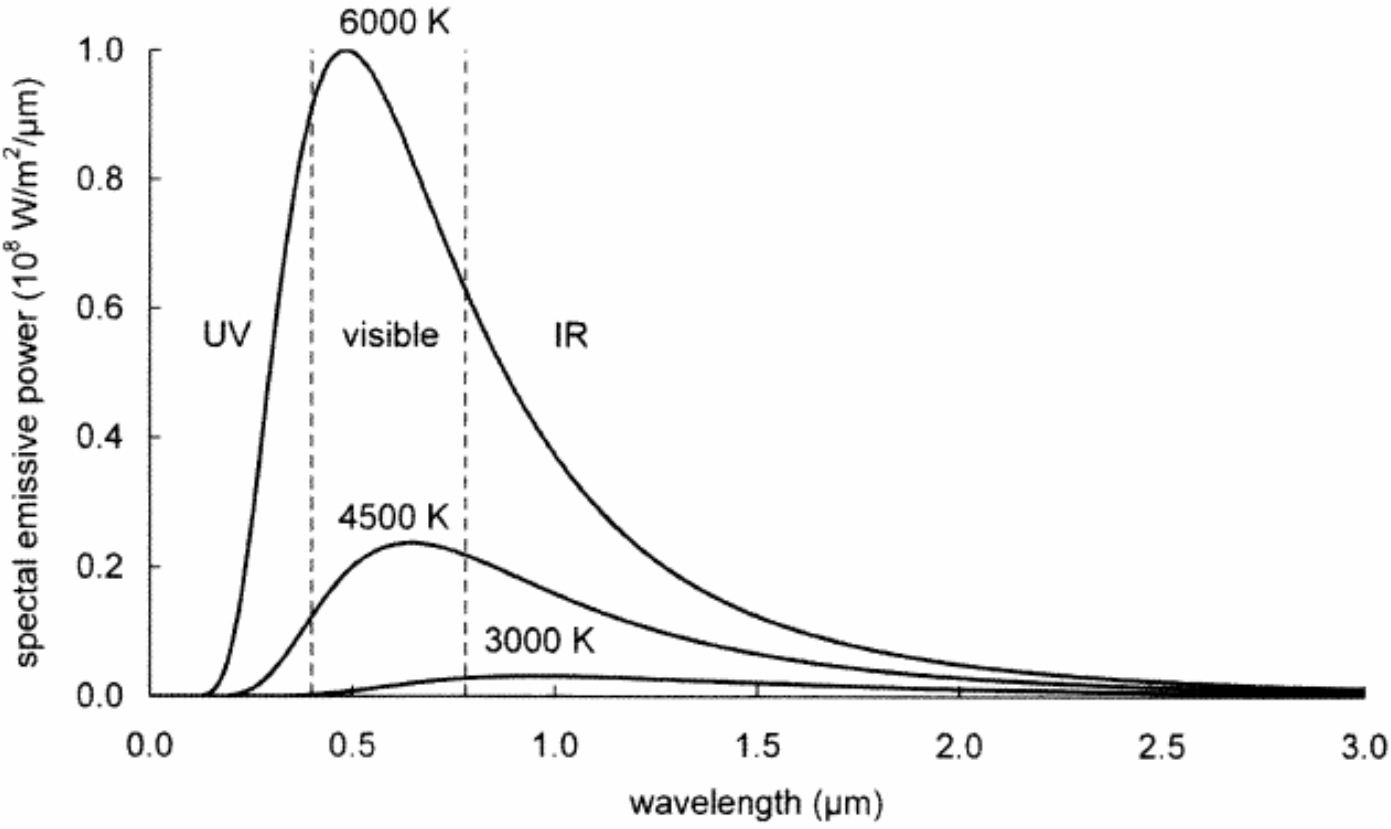


Figure 1.1. Radiation distributions from perfect blackbodies at three different temperatures, as would be observed at the surface of the blackbodies.

Solar spectrum approximated as a blackbody (Planck distribution law)

Photon flux density
= # photons with energy between E and E+dE per unit area per unit solid angle per unit time:

$$b_s(E) = \frac{2}{h^3c^2} \frac{E^2}{e^{E/kT} - 1} \, dE dA d\Omega$$

Energy flux density (irradiance): photon energy per unit area per unit solid angle per unit time

$$I(E) = Eb_s(E) = \frac{2}{h^3c^2} \frac{E^3}{e^{E/kT} - 1} \, dE dA d\Omega$$

- Rayleigh scattering (λ^{-4} dependence)
- Scattering by aerosols and dust particles
- Absorption by atmospheric gases (O_2, O_3, H_2O, CO_2)

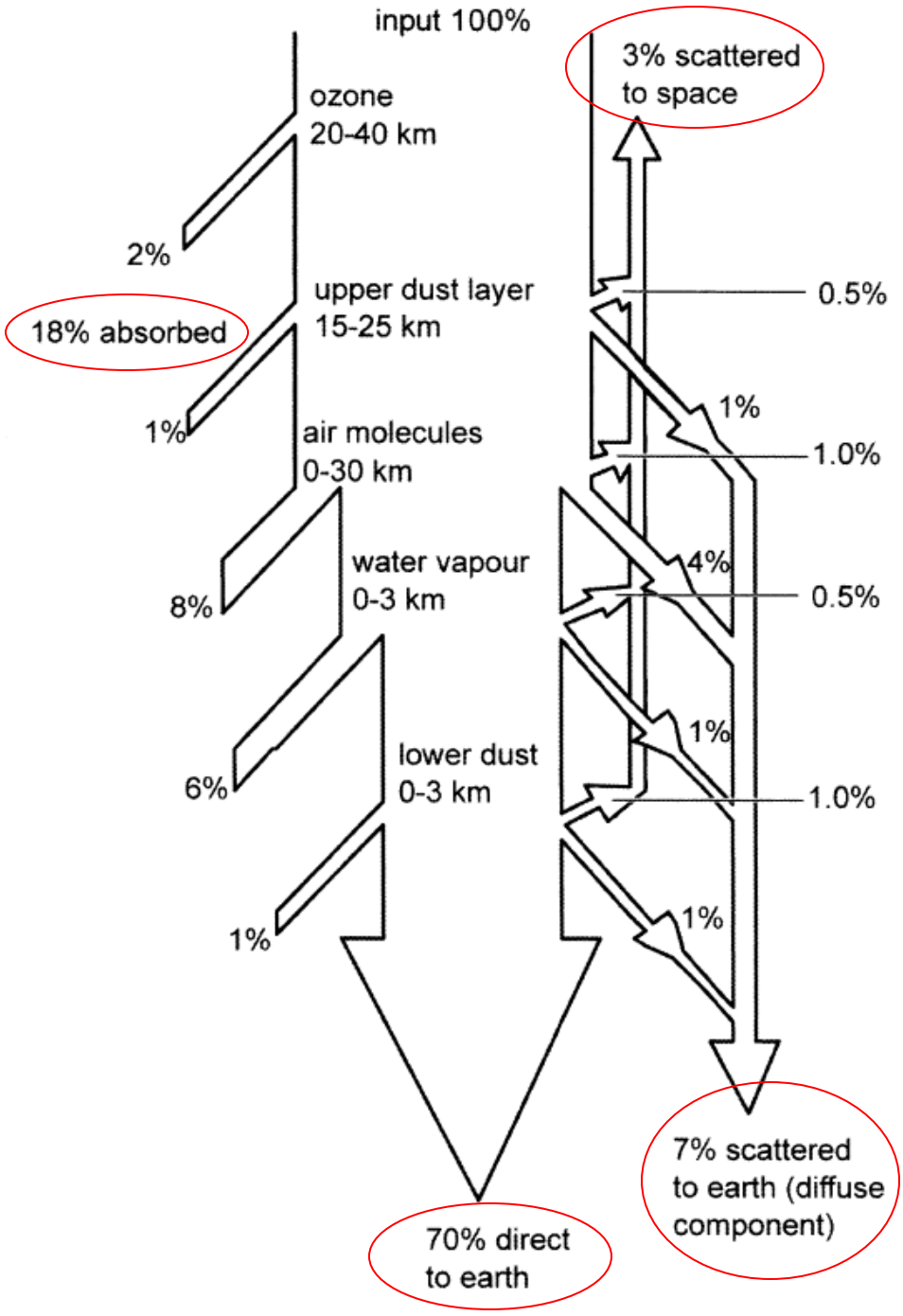


Figure 1.14. Typical AM1 clear sky absorption and scattering of incident sunlight (Used with permission of McGraw-Hill Companies, Hu, C. & White, R.M. (1983), Solar Cells: From Basic to Advanced Systems, McGraw-Hill, New York.).

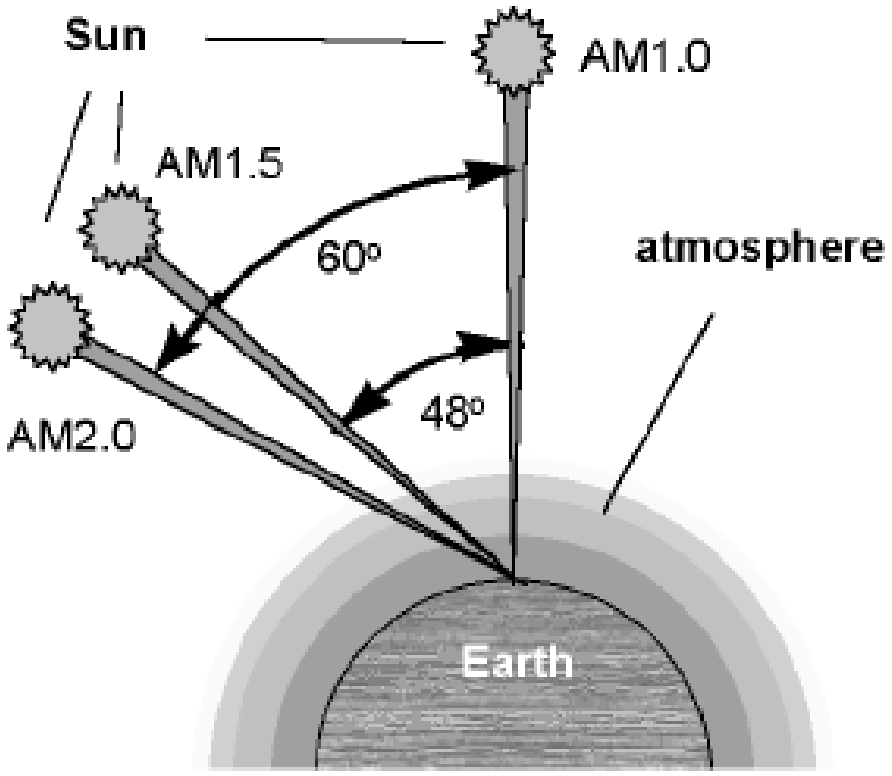
AM0: energy flux density outside the earth's atmosphere at the mean earth-sun distance

AM1.0: sunlight is attenuated ~20-30% due to scattering and absorption by the earth's atmosphere

Air mass = 1 / cosθ = factor of attenuation exceeding AM1.0

AM1.5 is a standard test condition for solar cells

AM1.5 spectra were chosen by ASTM "because they are representative of average conditions in the 48 contiguous states of the United States"



< AM1.5 : standard radiation >

Direct radiation: radiation straight from the Sun

Diffuse radiation: radiation scattered from the sky and surroundings (“albedo”)

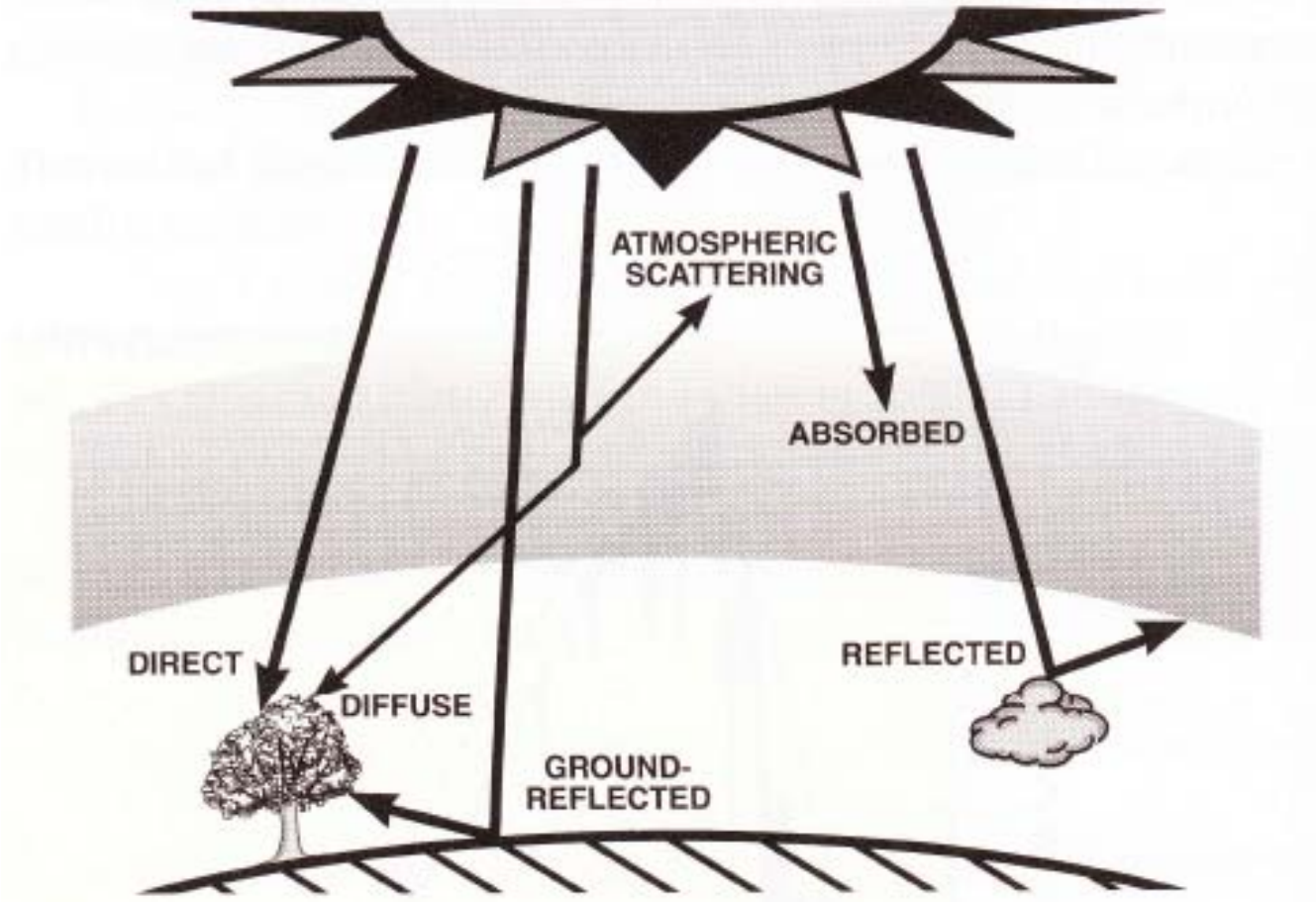


Fig. 2 The total global radiation on the ground has direct, scattered and reflective components.

Newport Catalogue

Must distinguish between direct versus diffuse spectrum
e.g., Concentrated versus unconcentrated PV

Direct = AM1.5D
Direct + diffuse = global spectrum (AM1.5G)

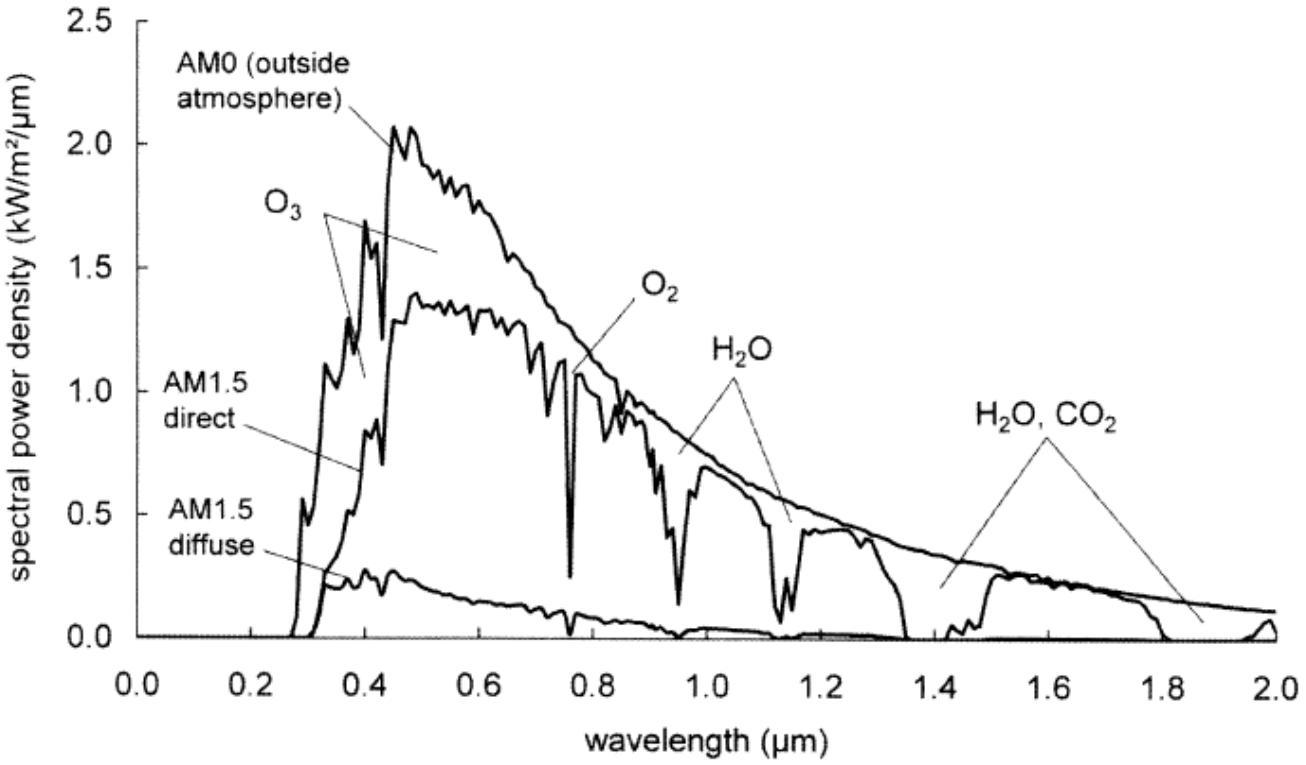


Figure 1.6. The spectral power density of sunlight, outside the atmosphere (AM0) and at the earth's surface (AM1.5), showing absorption from various atmospheric components.

Solar Condition	Standard
AM 0	ASTM E 490
AM 1	CIE Publication 85, Table 2
AM 1.5 D	ASTM E 891
AM 1.5 G	ASTM E 892
AM 1.5 G	CEI/IEC* 904-3

* Integration by modified trapezoidal technique
CEI = Commission Electrotechnique Internationale
IEC = International Electrotechnical Commission

Newport Catalogue

Details of the spectrum are available at
http://rredc.nrel.gov/solar/spectra/am1.5/

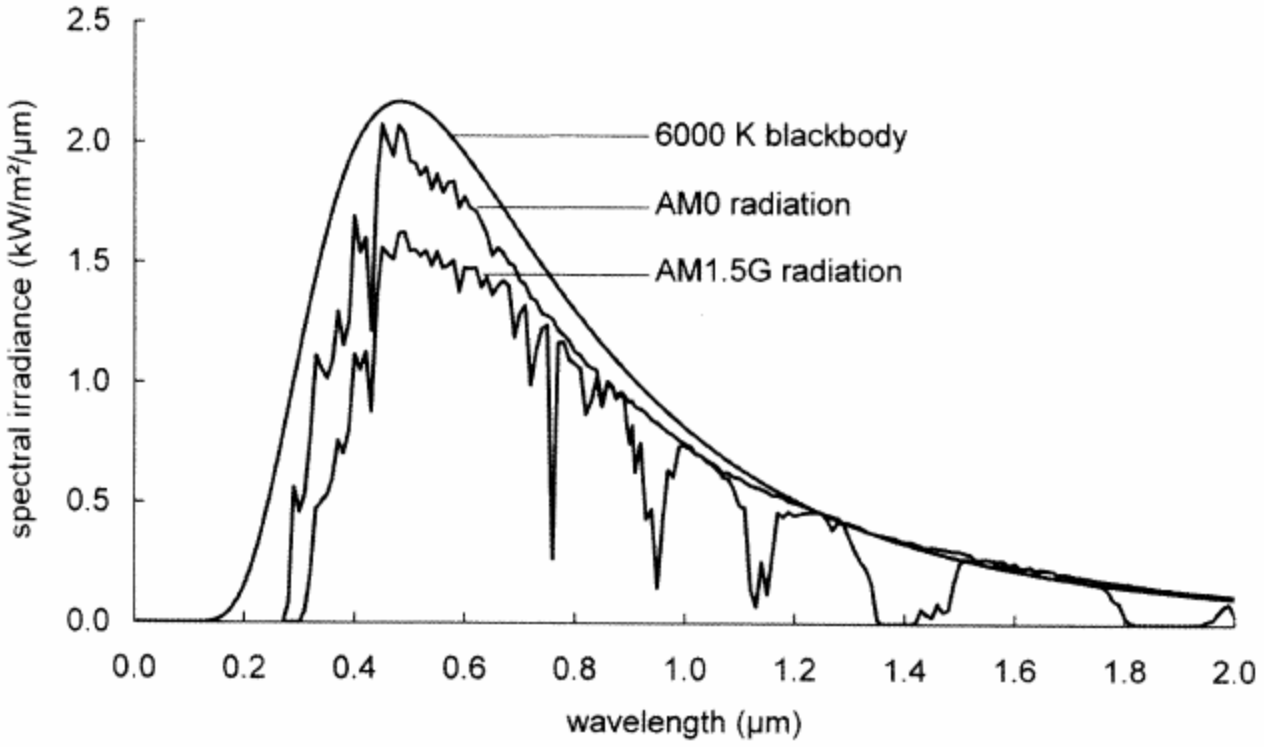


Figure 1.3. The spectral irradiance from a blackbody at 6000 K (at the same apparent diameter as the sun when viewed from earth); from the sun's photosphere as observed just outside earth's atmosphere (AM0); and from the sun's photosphere after having passed through 1.5 times the thickness of earth's atmosphere (AM1.5G).

Solar Constant = Total power density from integrated spectrum for AM0:

1353 ± 21 W/m^2 (NASA value given in ASTM E 490-73a)
1367 W/m^2 (World Metrological Organization (WMO) value)
1360 W/m^2 (commonly accepted value)

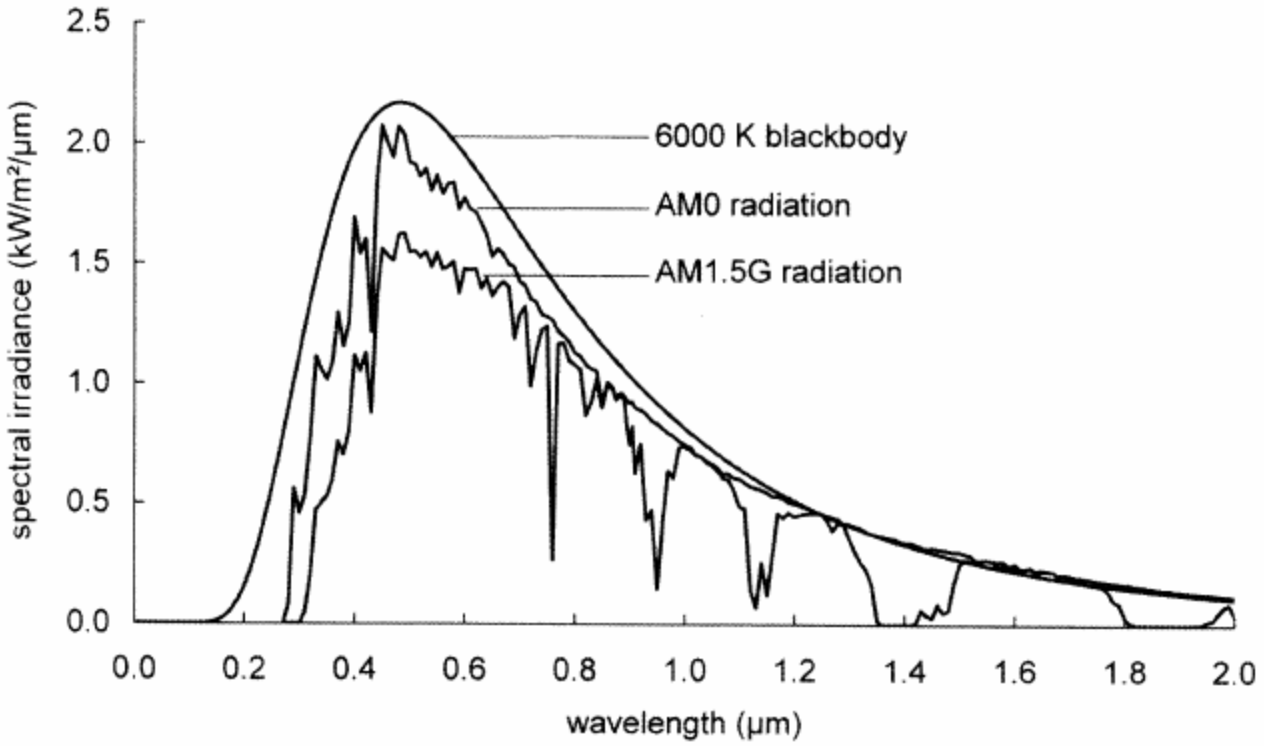


Figure 1.3. The spectral irradiance from a blackbody at 6000 K (at the same apparent diameter as the sun when viewed from earth); from the sun's photosphere as observed just outside earth's atmosphere (AM0); and from the sun's photosphere after having passed through 1.5 times the thickness of earth's atmosphere (AM1.5G).

Total power density from integrated spectrum
= 970 W/m^2 for AM1.5G

Standard test conditions (STC): AM 1.5G spectrum
1000W/m^2 = 100 mW/cm^2 (1 Sun)
25 °C

The output power specified for a solar cell is measured under the standard test conditions and denoted W_p

Testing performed at certified labs such as NREL

Table 1 Power Densities of Published Standards

Solar Condition	Standard	Power Density (Wm^{-2})		
		Total	250 - 2500 nm	250 - 1100 nm
	WMO Spectrum	1367		
AM 0	ASTM E 490	1353	1302.6	1006.9
AM 1	CIE Publication 85, Table 2		969.7	779.4
AM 1.5 D	ASTM E 891	768.3	756.5	584.7
AM 1.5 G	ASTM E 892	963.8	951.5	768.6
AM 1.5 G	CEI/IEC* 904-3	1000	987.2	797.5

* Integration by modified trapezoidal technique
CEI = Commission Electrotechnique Internationale
IEC = International Electrotechnical Commission

Newport Catalogue

Details of the spectrum are available at
http://rredc.nrel.gov/solar/spectra/am1.5/

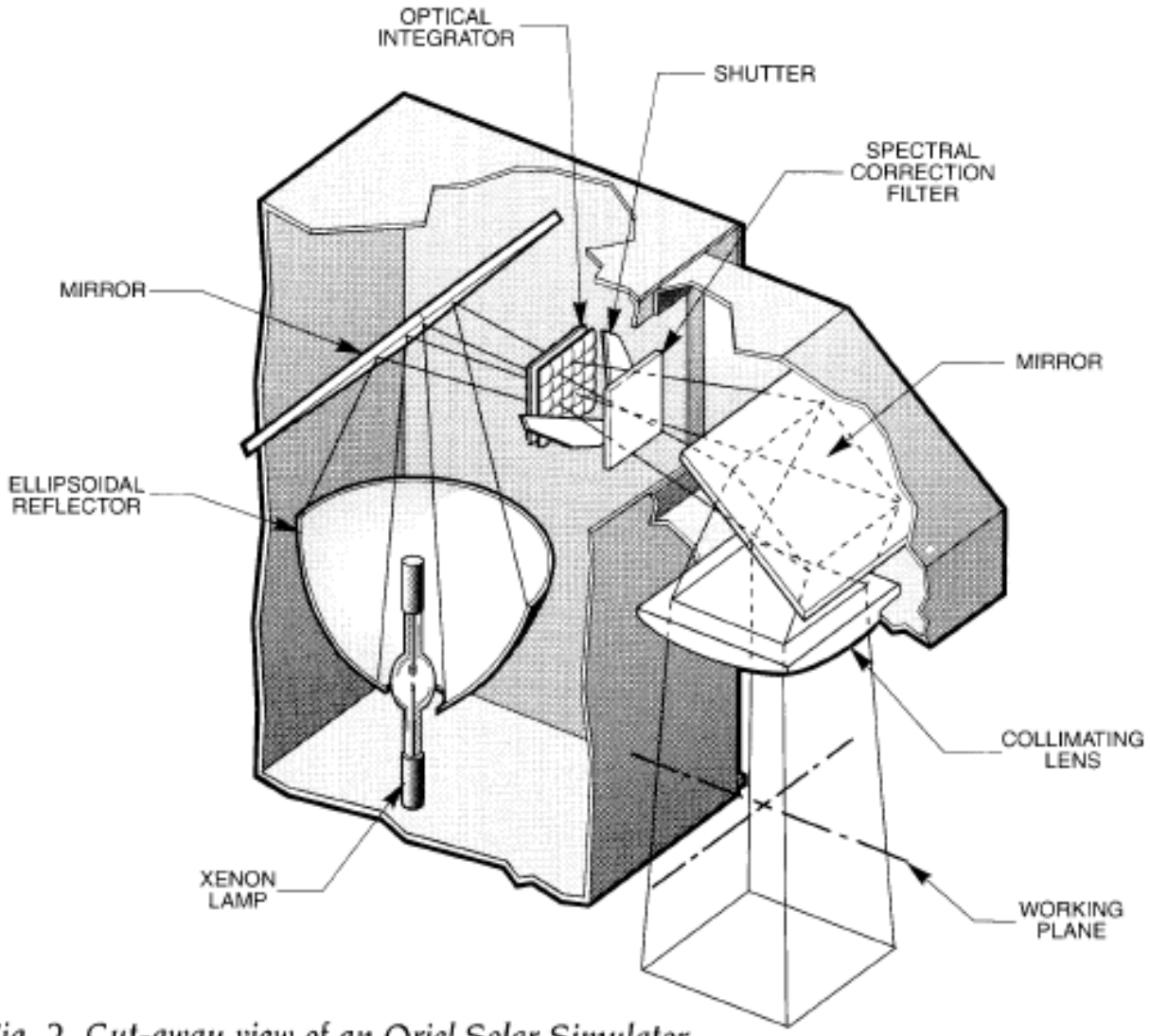


Fig. 2 Cut-away view of an Oriel Solar Simulator.

Newport Catalogue

Total power density from integrated spectrum:
1353 W/m^2 for AM0
970 W/m^2 for AM1.5G
768 W/m^2 for AM1.5D

However, solar radiation varies significantly with location, atmospheric conditions, cloud cover, aerosol content, ozone, time of day, Earth-Sun distance, solar activity, etc.

<u>Daily variation</u>:

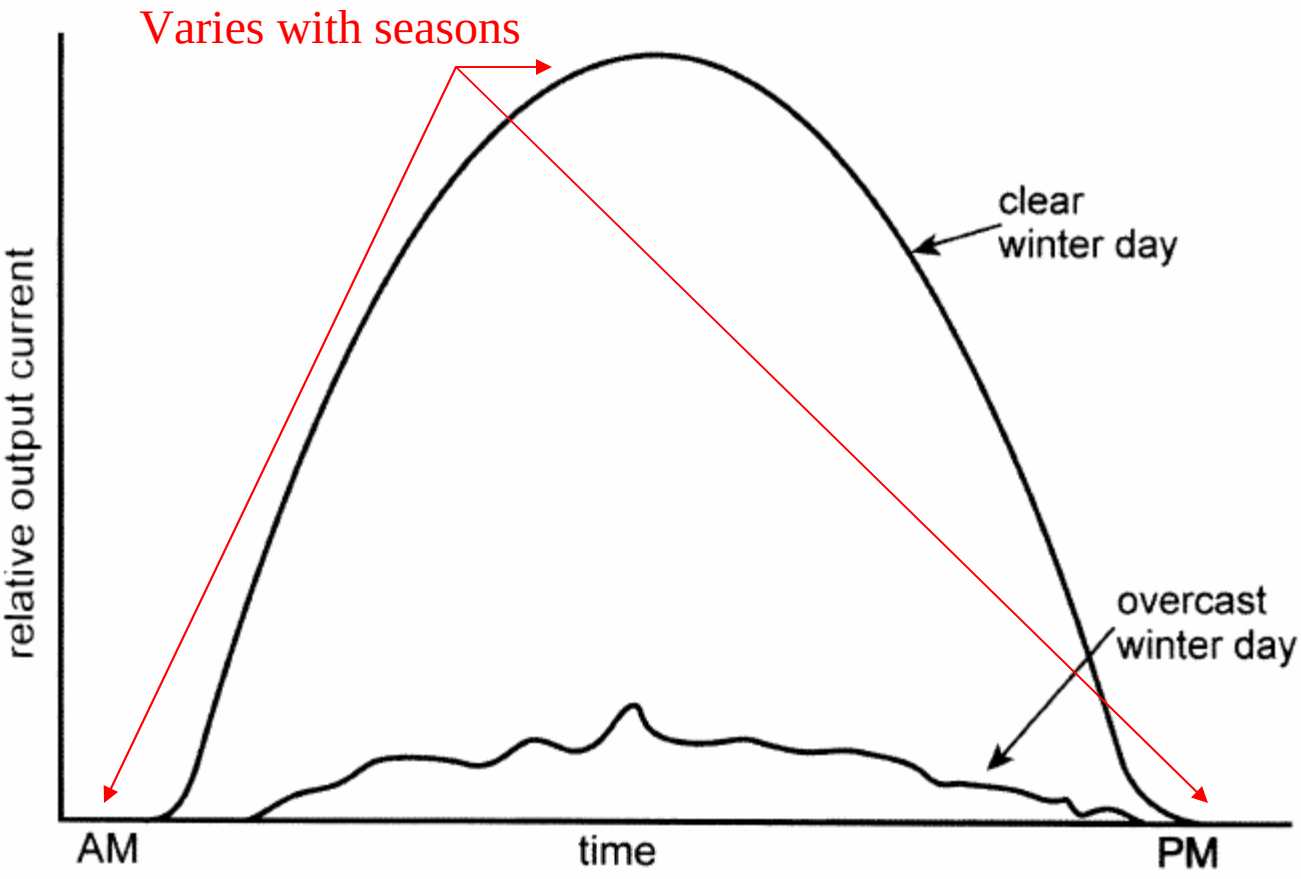
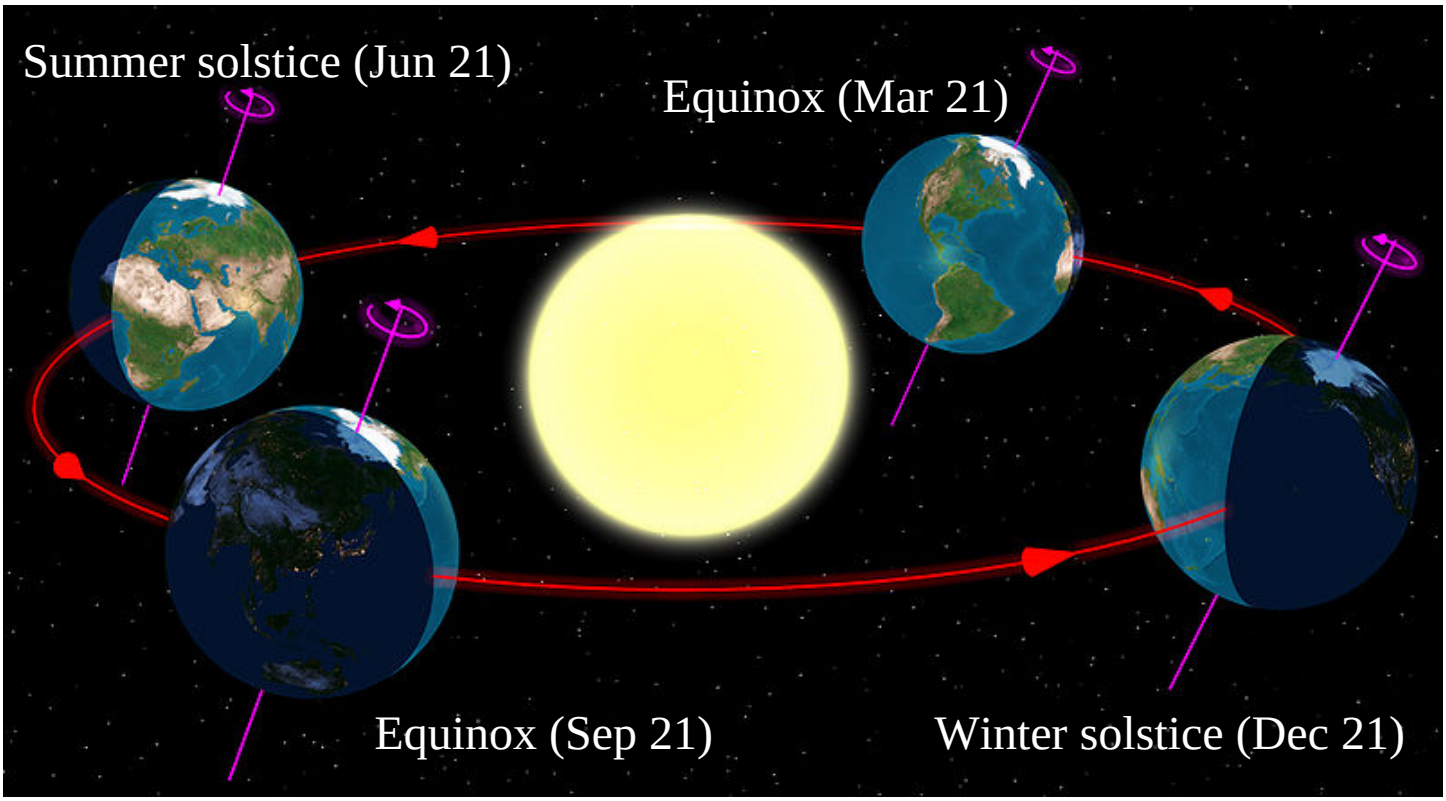


Figure 1.16. Relative output current from a photovoltaic array on a sunny and a cloudy winter's day in Melbourne (38°S) with an array tilt angle of 60° (after Mack, 1979).

Seasonal and Latitude Variation:

e.g., for the Northern hemisphere



http://en.wikipedia.org/wiki/File:North_season.jpg

Seasonal and Latitude Variation:

e.g., 35° S latitude

Equinoxes:	Mar 21 and Sept 23
	Altitude at noon = 90° - latitude
Summer Solstice:	Dec 22
Winter Solstice:	Jun 21

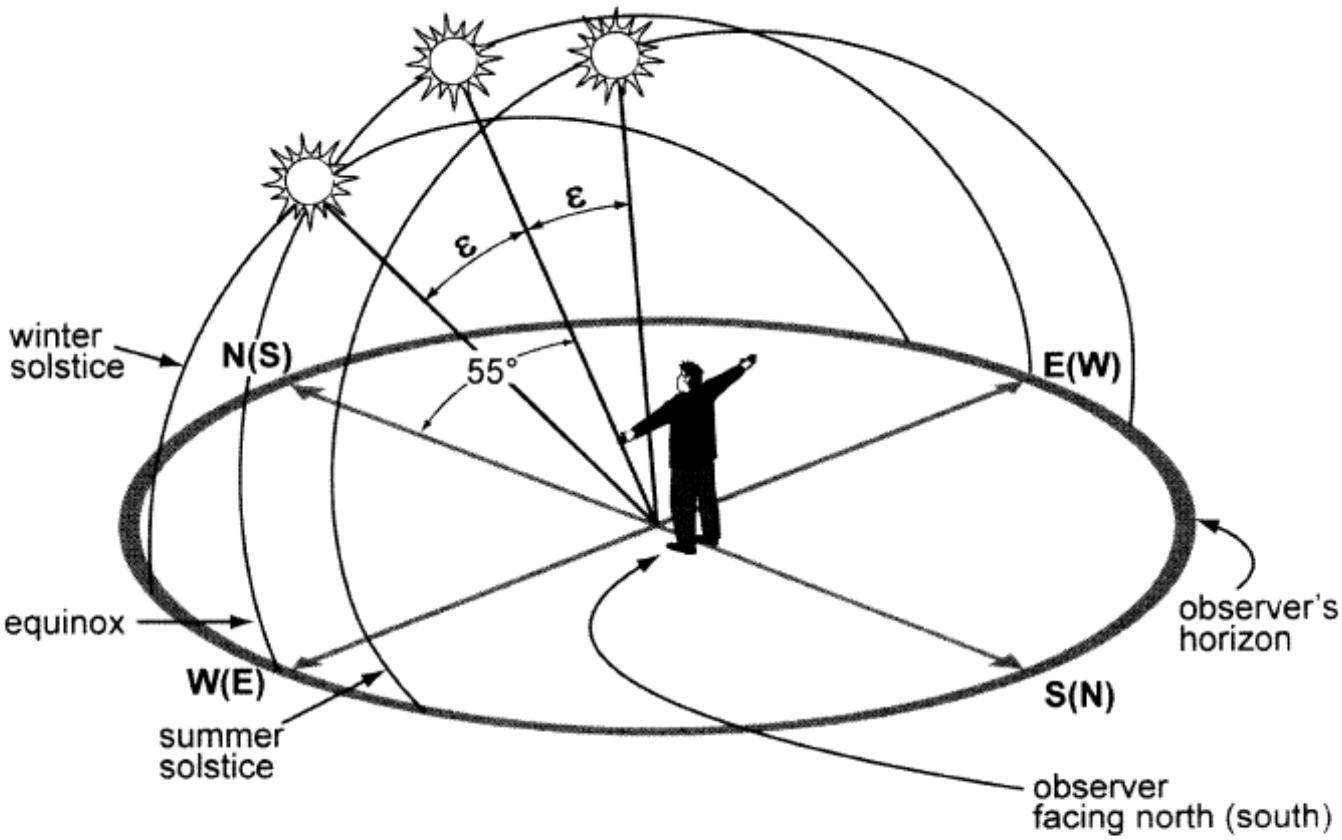
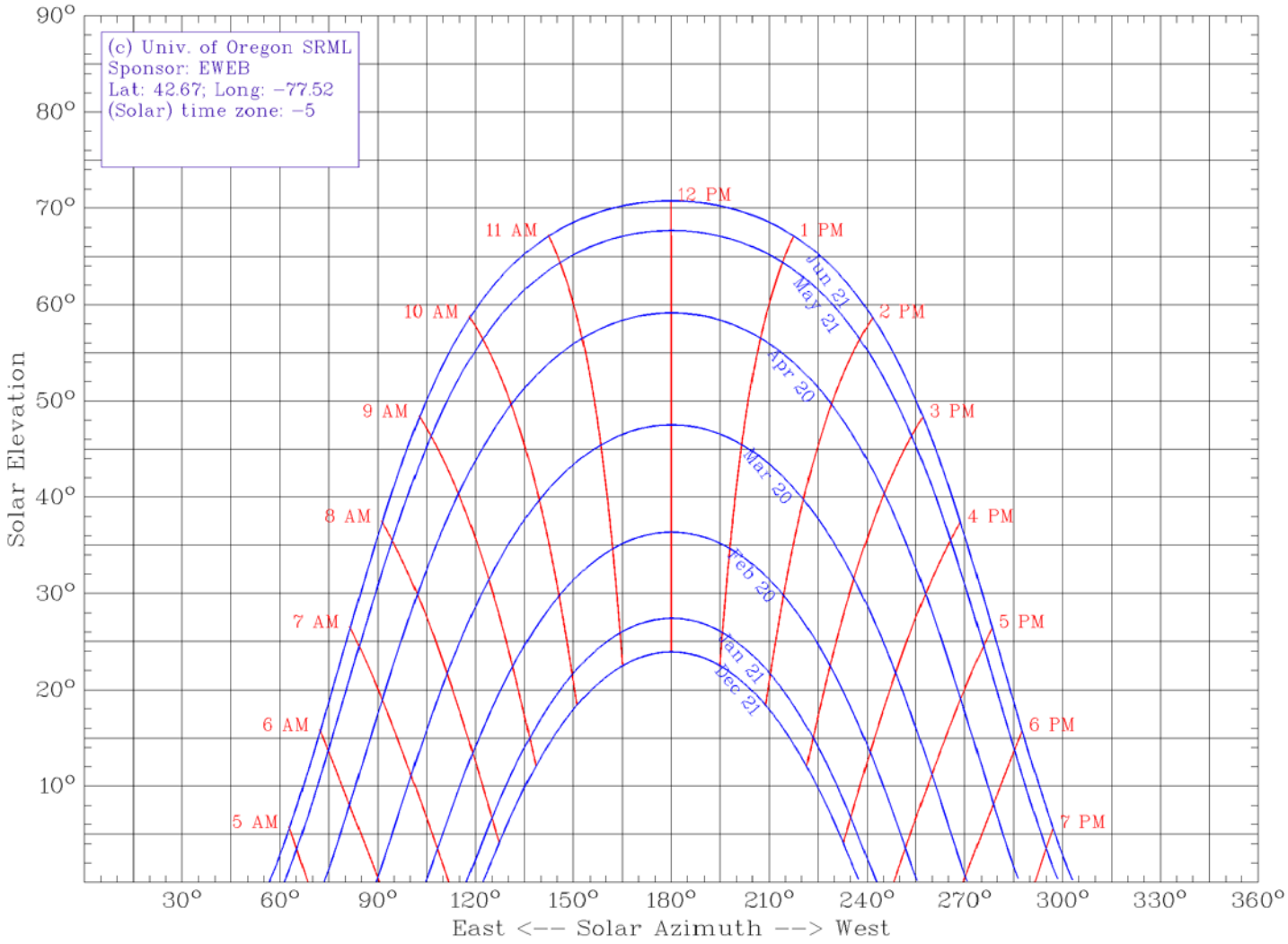


Figure 1.10. Apparent motion of the sun for an observer at 35°S (or N), where ε is the inclination of the earth's axis of rotation relative to its plane of revolution about the sun (= 23°27' = 23.45°).

Trajectory Maps

http://solardat.uoregon.edu/SunChartProgram.php



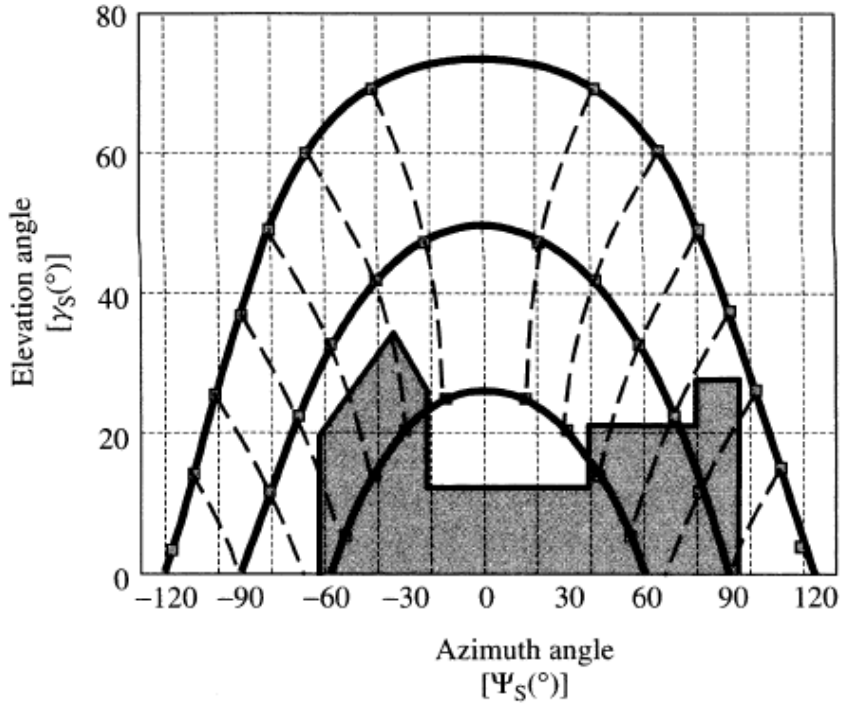
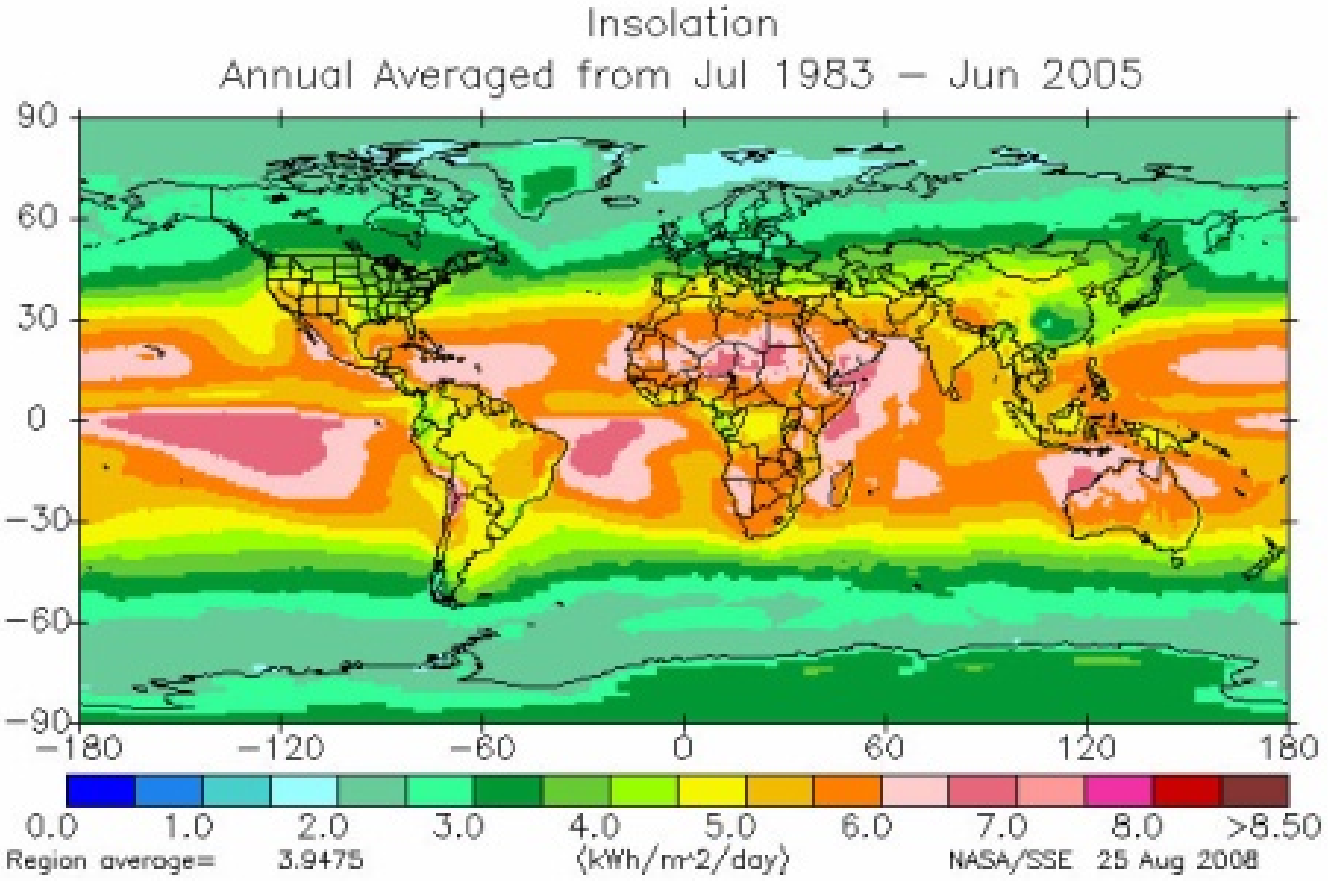


Figure 20.18 Sun's trajectory map corresponding to a latitude $\phi = 40.5°$, with a skyscraper superimposed on the map. For example, on the winter solstice, shadows occur from sunrise to about 10:30 (solar time) and from 14:30 to sunset

Insolation:

Average amount of sunlight on Earth taking account of atmospheric absorption, latitude, cloud cover, length of day, season, etc.

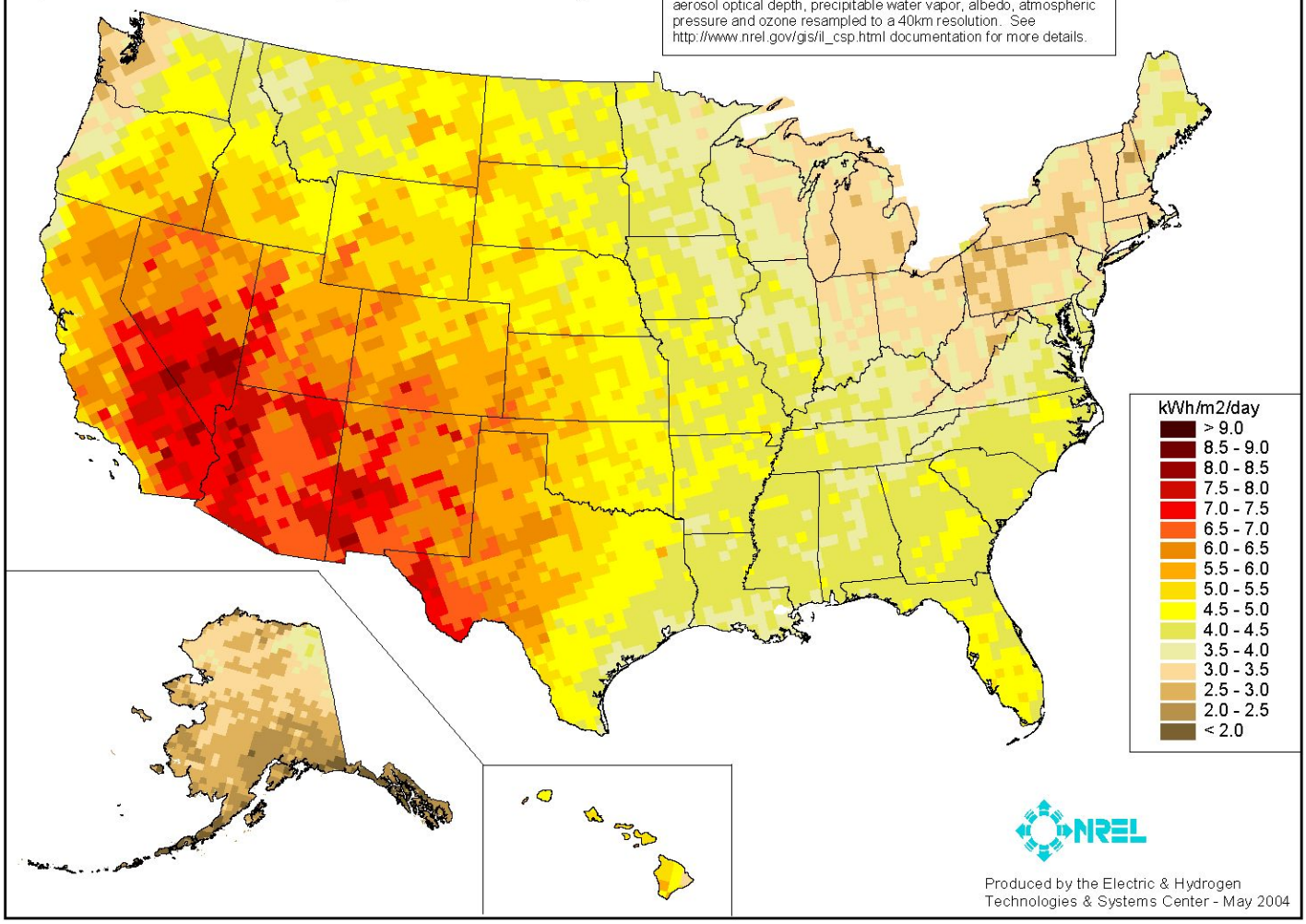
kWh / m^2 / day = # hours per day of STC equivalent sunshine



Direct Normal Solar Radiation (Two-Axis Tracking Concentrator)

Annual

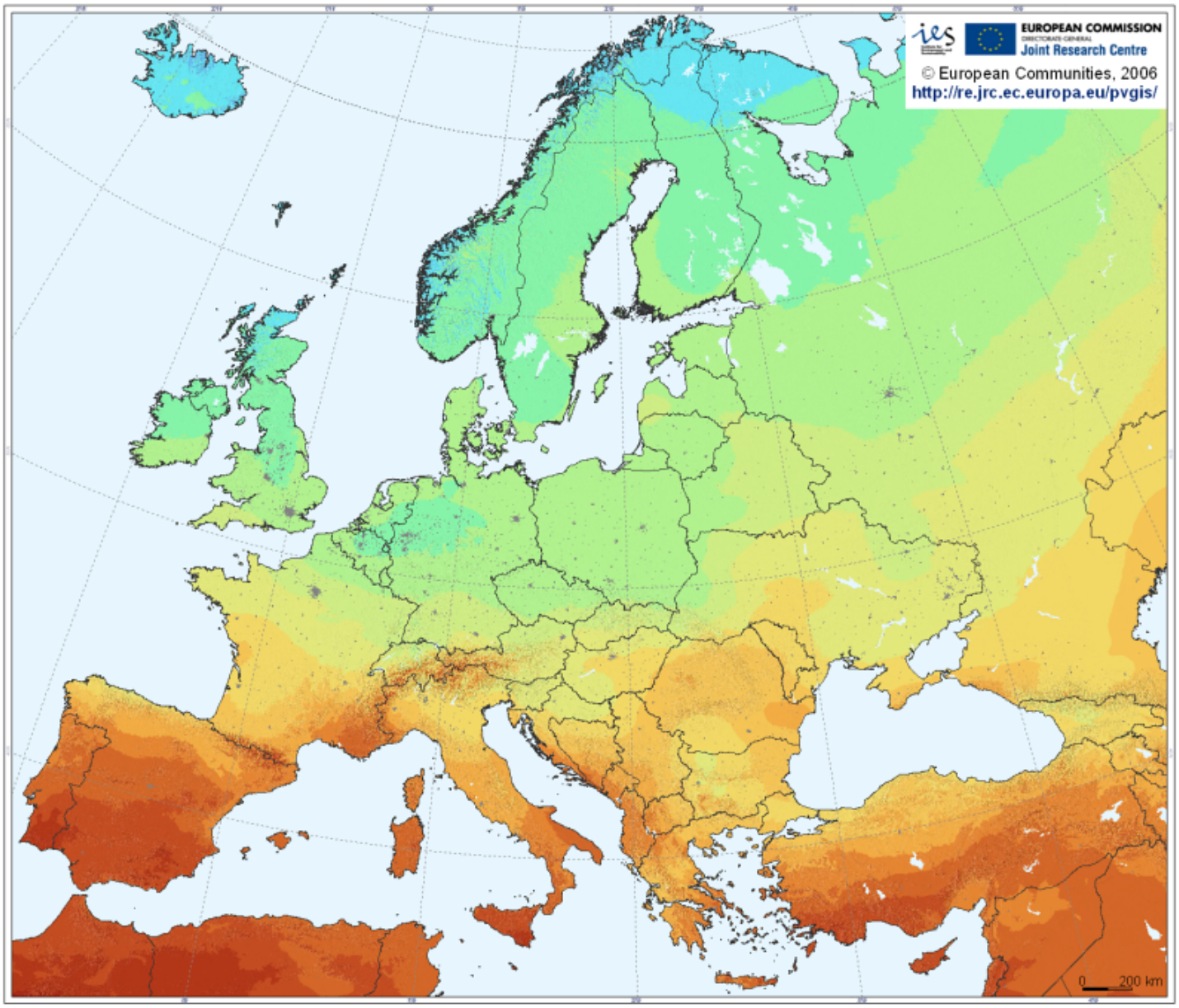
Model estimates of monthly average daily total radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone resampled to a 40km resolution. See http://www.nrel.gov/gis/il_csp.html documentation for more details.



NREL

Produced by the Electric & Hydrogen Technologies & Systems Center - May 2004

Photovoltaic Solar Electricity Potential in European Countries



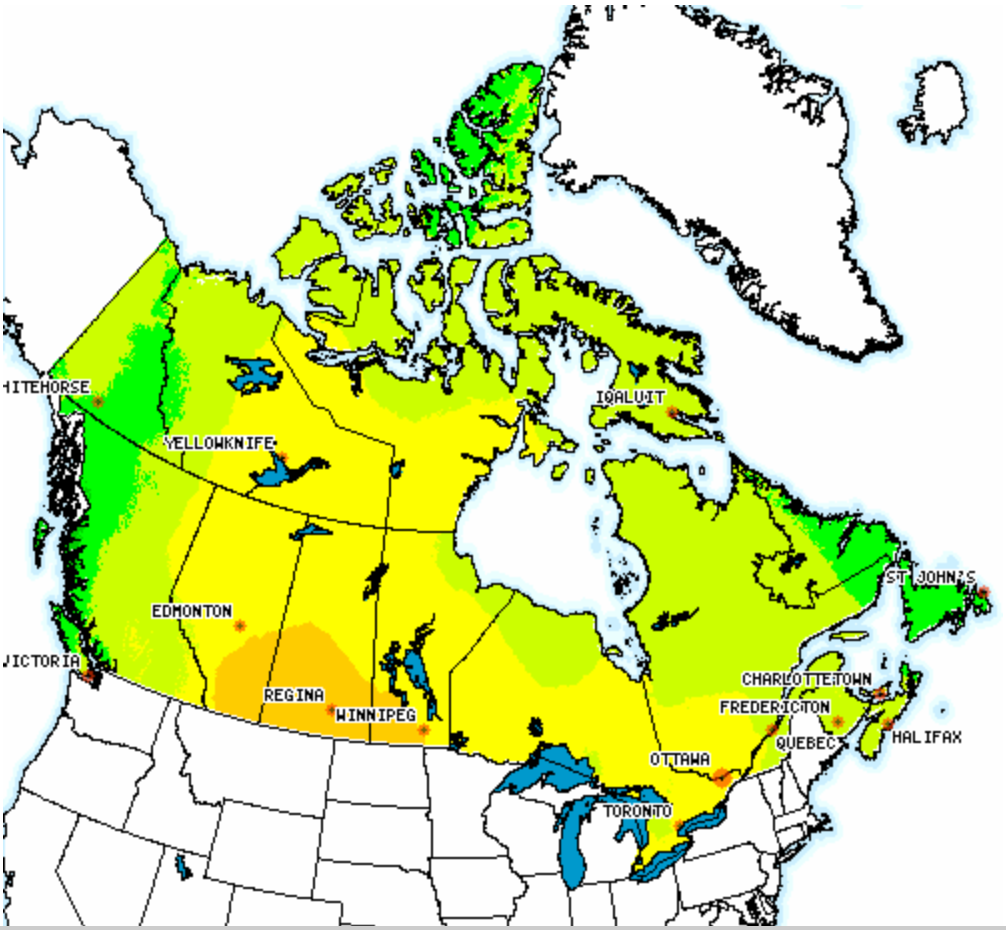
Yearly sum of global irradiation incident on optimally-inclined south-oriented photovoltaic modules

Global irradiation [kWh/m²]
<600 800 1000 1200 1400 1600 1800 2000 2200>

Yearly sum of solar electricity generated by 1 kWp system with optimally-inclined modules and performance ratio 0.75

<450 600 750 900 1050 1200 1350 1500 1650>
Solar electricity [kWh/kWp]

Natural Resources Canada:
https://glfc.cfsnet.nfis.org/mapserver/pv/index_e.php



Legend

Mean daily global insolation (MJ/m², kWh/m²) 2 Axis sun-tracking Annual

- ***0-0.8 kWh/m²***
- ***0.8-1.7***
- ***1.7-2.5***
- ***2.5-3.3***
- ***3.3-4.2***
- ***4.2-5***
- ***5-5.8***
- ***5.8-6.7***
- ***6.7-8.5***
- ***8.5-9.2***
- ***9.2+***

Effect of solar cell tilt:

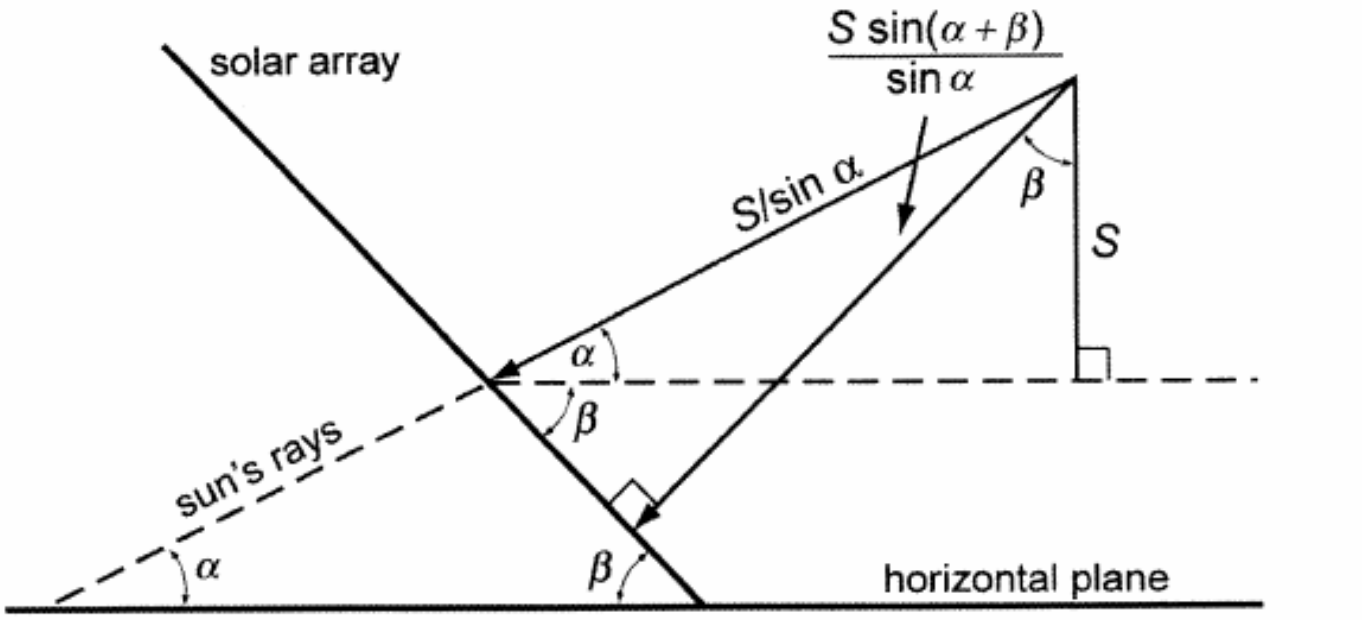
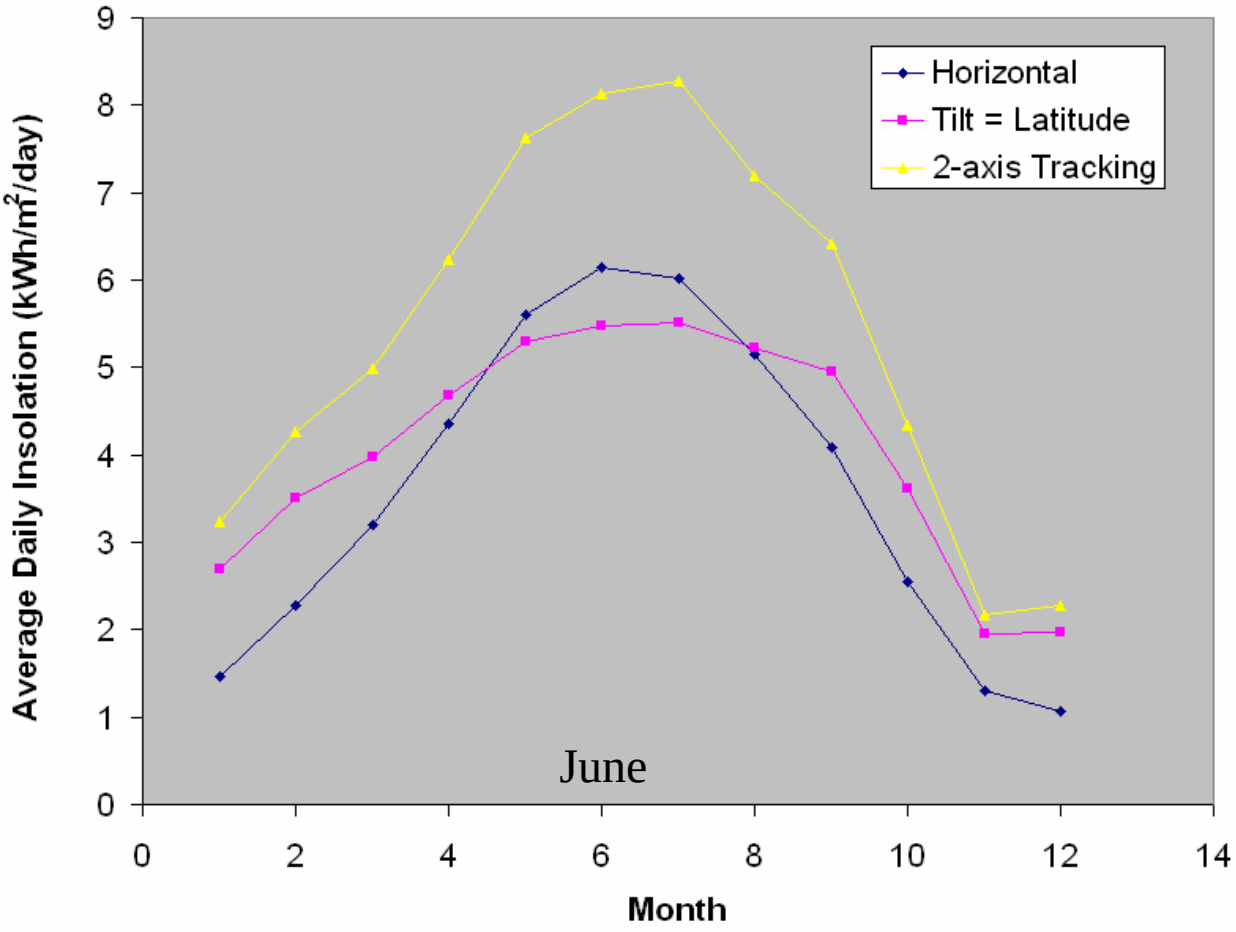


Figure 1.15. Light incident on a surface tilted to the horizontal (after Mack, 1979).

Insolation at angle (altitude = latitude) α : $S_\alpha = S / \sin\alpha$

Insolation on panel tilted at angle β : $S_\beta = (S / \sin\alpha) \sin(\alpha + \beta)$

α = altitude of the Sun; changes daily and monthly


Horizontal
Tilt = Latitude
2-axis Tracking
June
Average Daily Insolation (kWh/m2/day)
Month
0
1
2
3
4
5
6
7
8
9
0
2
4
6
8
10
12
14