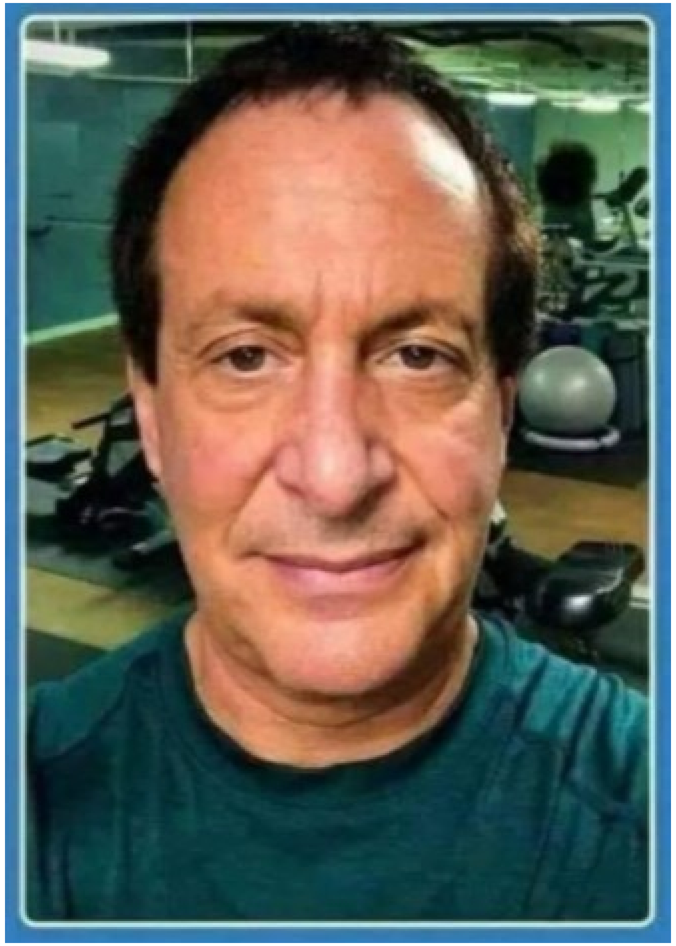
SOLAR RADIATION

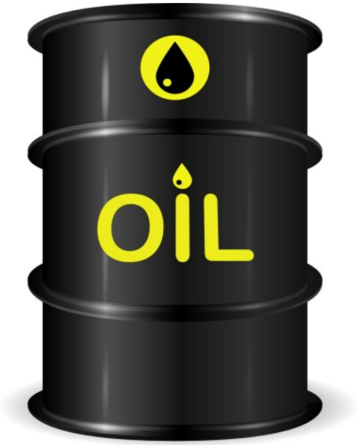
Dr. OSAMA AYADI

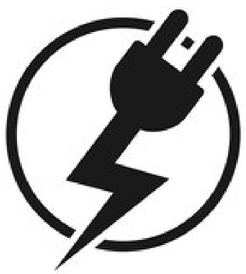
SOLAR DRYER!!

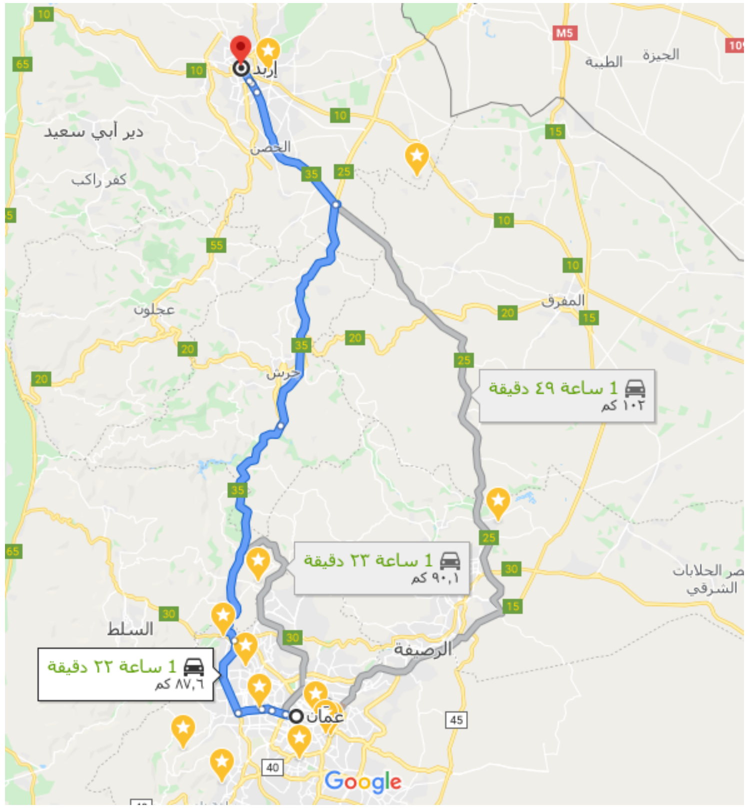
قام بنشر إعلان عن بيع "مجفف ملابس" يعمل بالطاقة الشمسية بسعر 49.95 دولار ، والاستلام بعد ثلاثة أشهر ..
وبناءً على الإعلان المنشور حصل على حجز لجهازه بقيمة عشرة ملايين دولار..
وعند الإستلام فوجئ الزبائن أن المنتج عبارة عن "حبل غسيل" !!
رفعت حماية المستهلك عليه قضية نصب واحتيال..إلا أن الحكم صدر لصالحه..وكان من حيثيات الحكم:
"إن نشر الملابس على الحبل يعتبر تجفيفاً بالطاقة الشمسية" ..
وحصل ستيف على تعويض قيمته 500 ألف دولار رد شرف من حماية المستهلك..بالإضافة لقيمة الحجز الذي قدمه الزبائن..



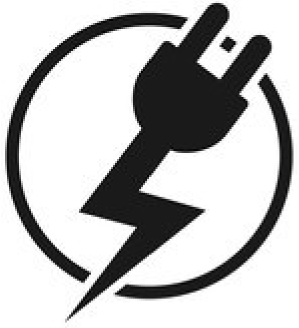
ENERGY SOURCE → ENERGY CONVERSION → DEMAND/ SERVICE

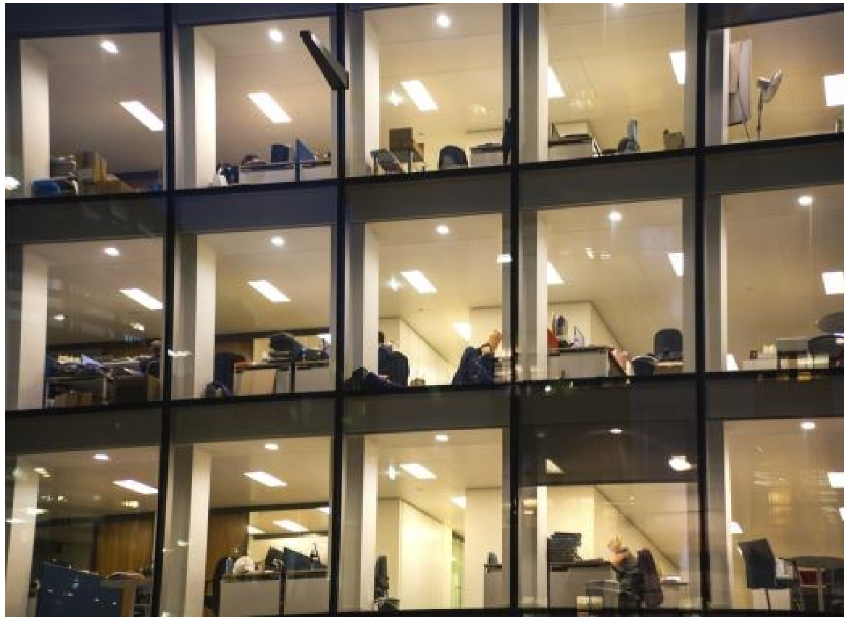


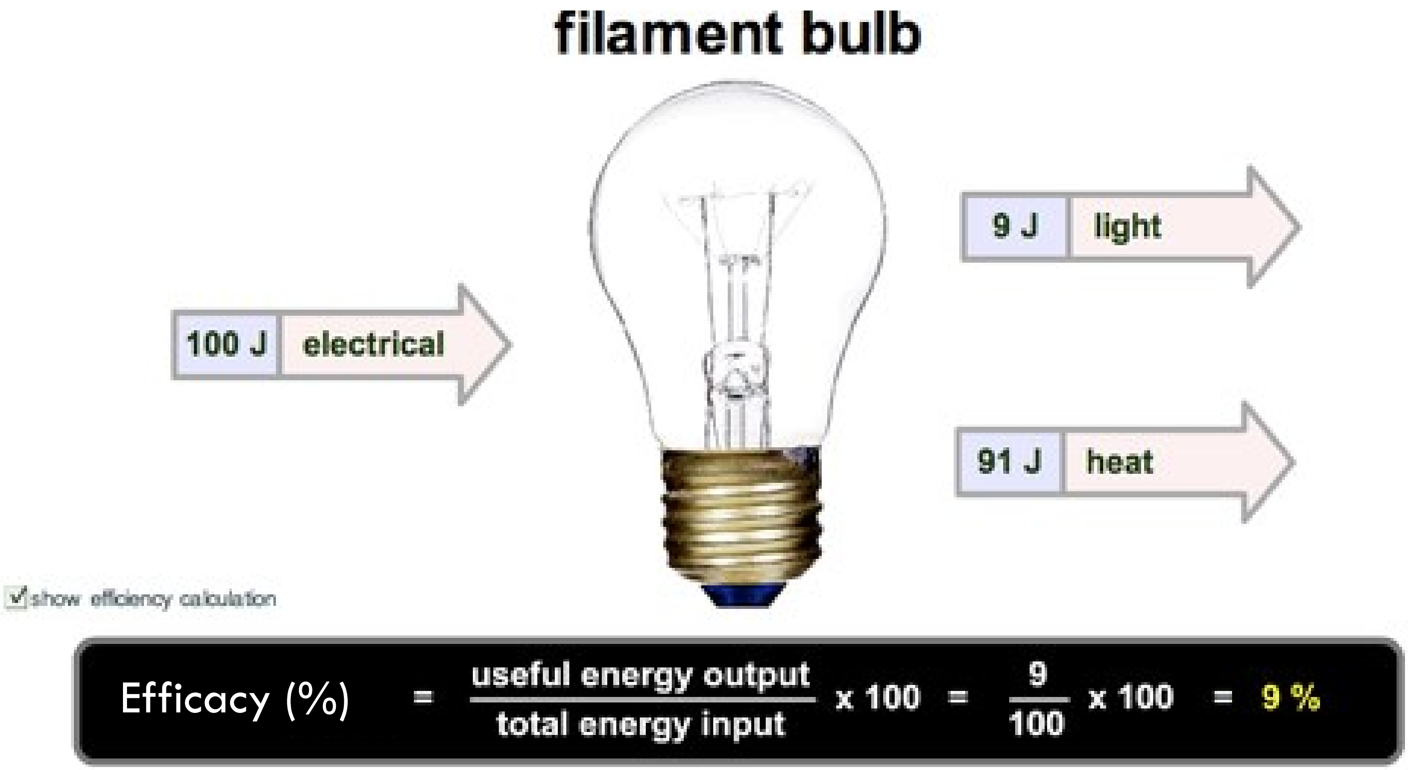




ELEC-TRICITY → ENERGY CONVERSION → DEMAND/ SERVICE






filament bulb
100 J electrical
9 J light
91 J heat
show efficiency calculation
Efficacy (%) = useful energy output / total energy input x 100 = 9 / 100 x 100 = 9 %

EXAMPLE:

A 100 W bulb is switched ON for 8 hours. If the price of electricity is 50 fils / kWh, what is the cost of energy consumed during that period?

Solution:

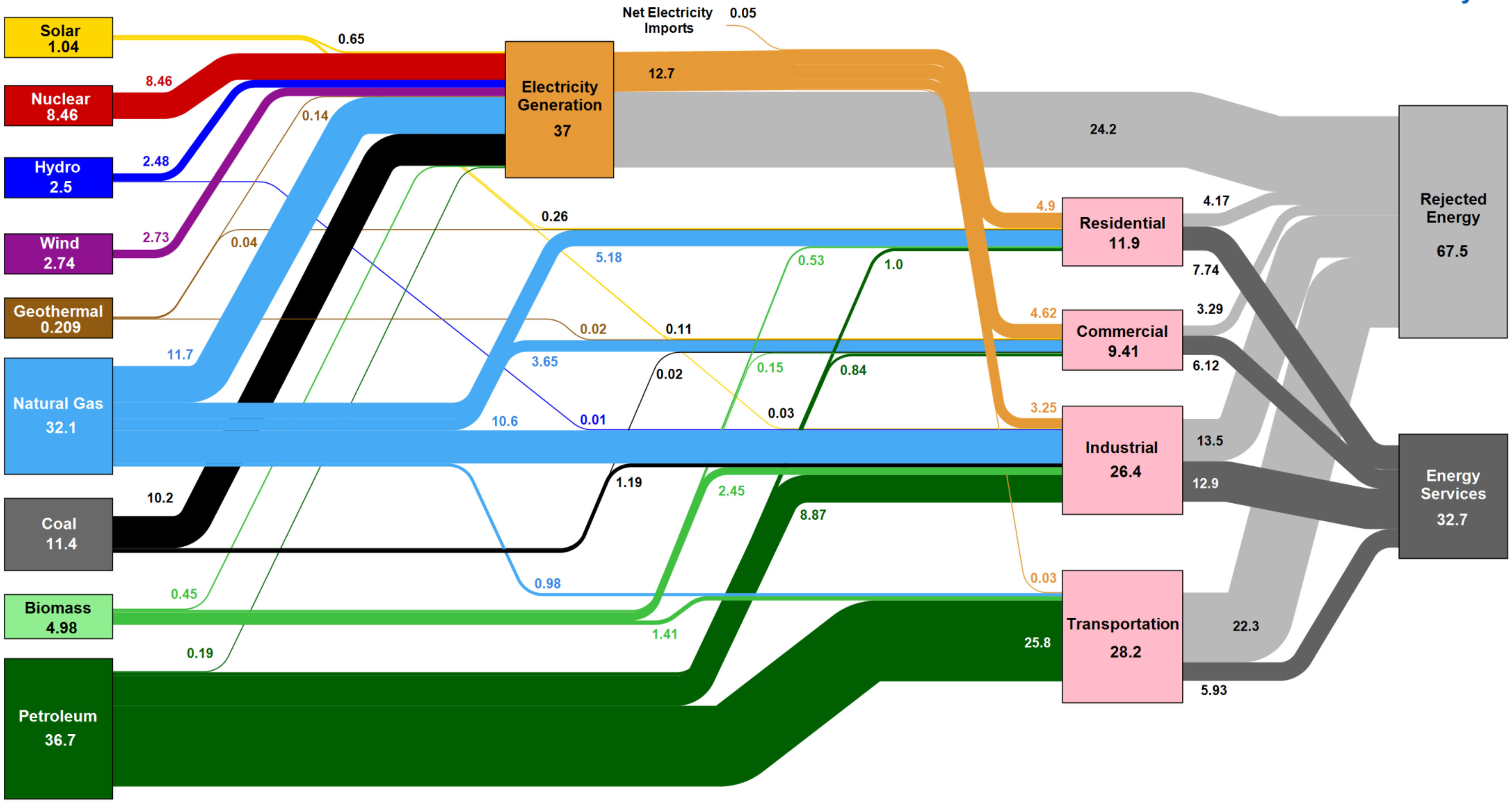
					

All bulbs provide about 850 lumens of light.

COST OF BULB		INCANDESCENT BULB	HALOGEN	COMPACT FLUORESCENT (CFL)	LIGHT EMITTING DIODE (LED)
	Life of bulb (how long it will light)	1,000 hours	3,000 hours	10,000 hours	25,000 hours
	Number of bulbs to get 25,000 hours	25 bulbs	8.3 bulbs	2.5 bulbs	1 bulb
x	Price per bulb	$0.50	$3.00	$3.00	$15.00
=	**Cost of bulbs for 25,000 hours of light**				
COST OF ELECTRICITY		**INCANDESCENT BULB**	**HALOGEN**	**COMPACT FLUORESCENT (CFL)**	**LIGHT EMITTING DIODE (LED)**
	Total Hours	25,000 hours	25,000 hours	25,000 hours	25,000 hours
x	Wattage	60 watts = 0.060 kW	43 watts = 0.043 kW	13 watts = 0.013 kW	12 watts = 0.012 kW
=	Total kWh consumption				
x	Price of electricity per kWh	$0.12	$0.12	$0.12	$0.12
=	**Cost of Electridity**				
LIFE CYCLE COST		**INCANDESCENT BULB**	**HALOGEN**	**COMPACT FLUORESCENT (CFL)**	**LIGHT EMITTING DIODE (LED)**
	Cost of bulbs				
+	Cost of electricity				
=	**Life cycle cost**				

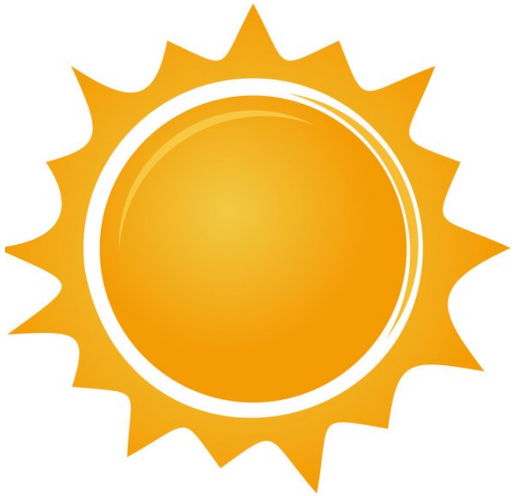
Estimated U.S. Energy Consumption in 2019: 100.2 Quads

Lawrence Livermore National Laboratory

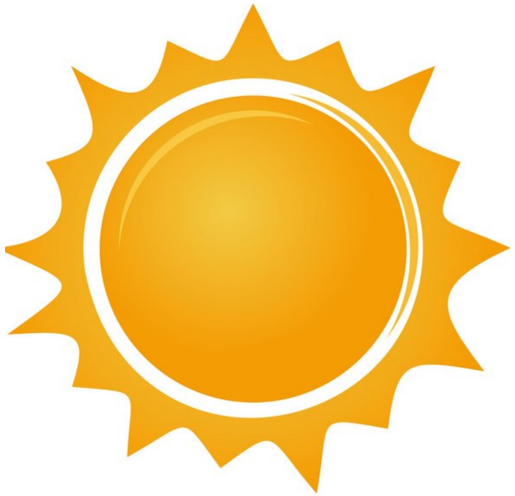


Source: LLNL March, 2020. Data is based on DOE/EIA MER (2019). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector and 49% for the industrial sector, which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

ENERGY SOURCE → ENERGY CONVERSION → DEMAND/ SERVICE



ENERGY SOURCE



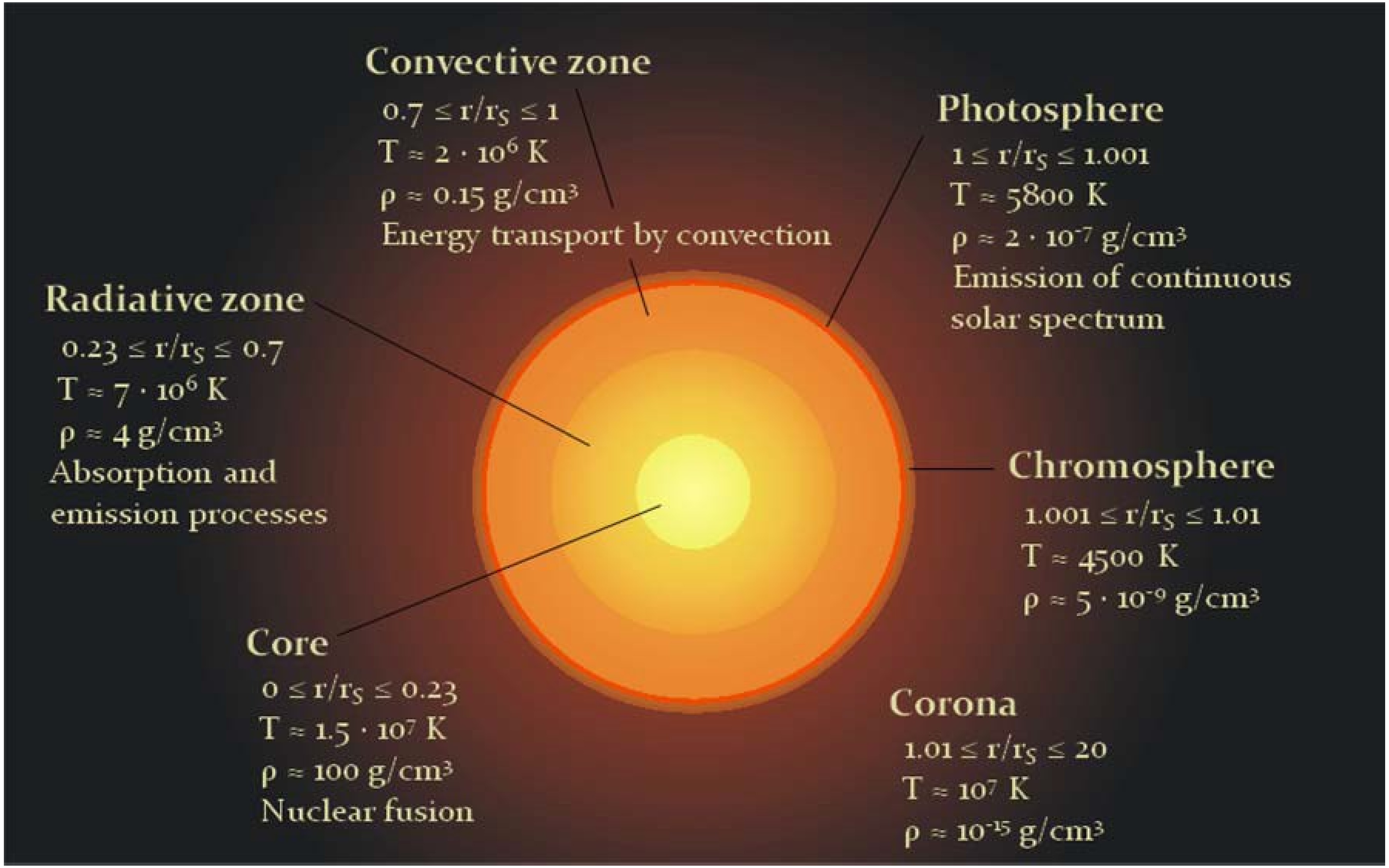
1. QUANTITY
2. DIRECTION
3. PHYSICS

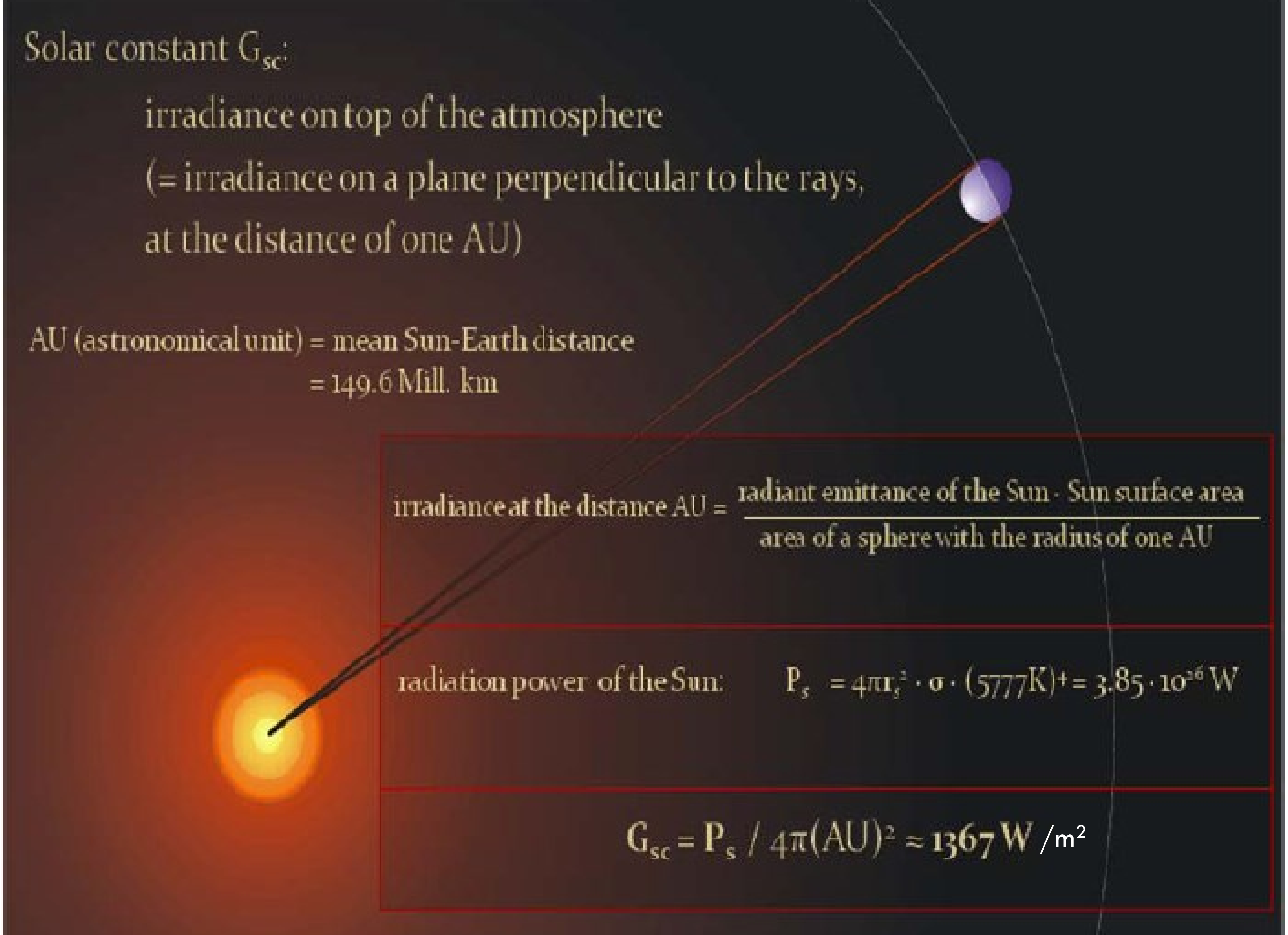
SOLAR RADIATION

- How much solar energy reaches the ground?
- Where to find and how to read solar radiation data?
- Slope and orientation of solar collectors
- Shadow effects

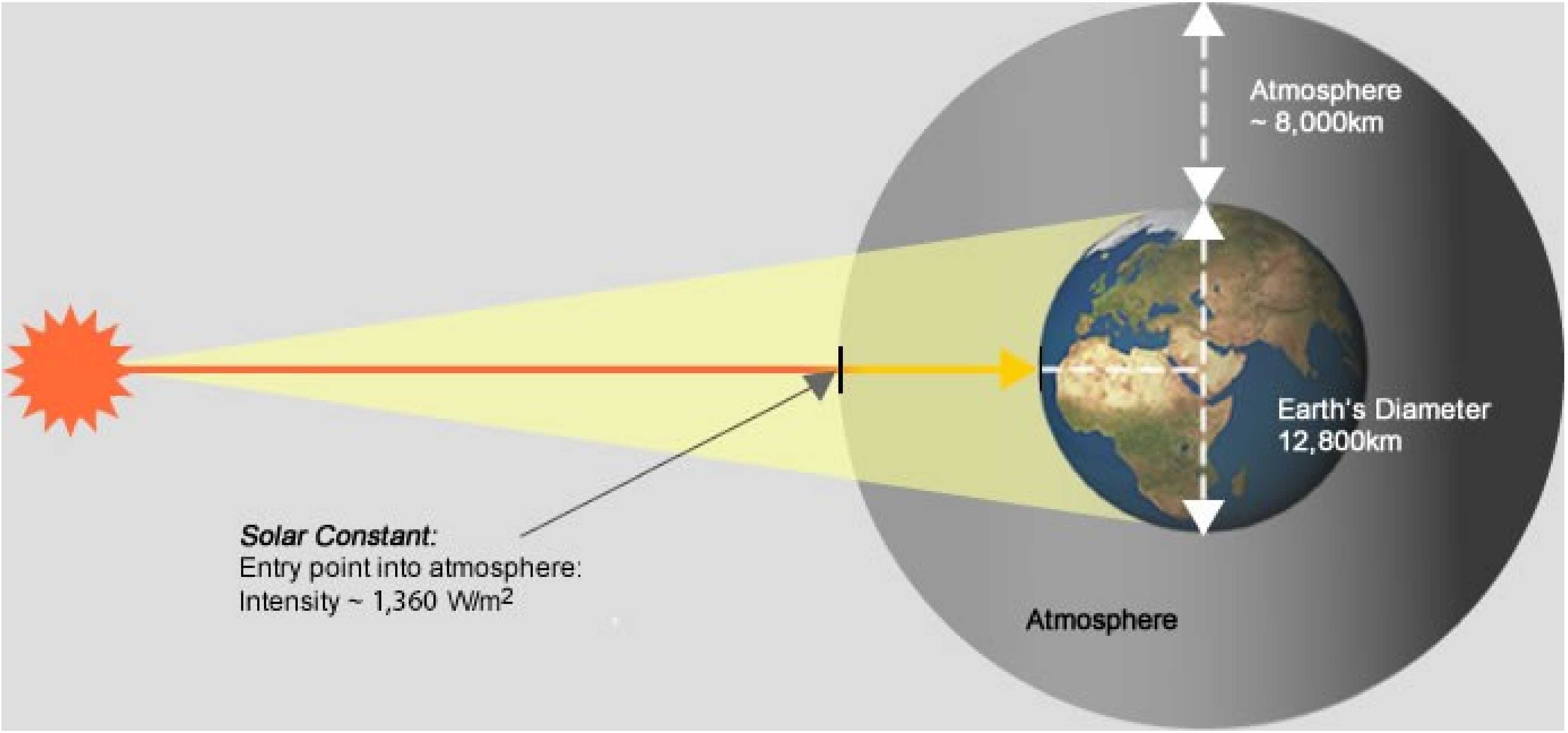
1. HOW MUCH SOLAR ENERGY REACHES THE GROUND?

1. THE SUN


Convective zone
$0.7 \leq r/r_S \leq 1$
$T \approx 2 \cdot 10^6$ K
$\rho \approx 0.15$ g/cm³
Energy transport by convection
Photosphere
$1 \leq r/r_S \leq 1.001$
$T \approx 5800$ K
$\rho \approx 2 \cdot 10^{-7}$ g/cm³
Emission of continuous solar spectrum
Radiative zone
$0.23 \leq r/r_S \leq 0.7$
$T \approx 7 \cdot 10^6$ K
$\rho \approx 4$ g/cm³
Absorption and emission processes
Chromosphere
$1.001 \leq r/r_S \leq 1.01$
$T \approx 4500$ K
$\rho \approx 5 \cdot 10^{-9}$ g/cm³
Core
$0 \leq r/r_S \leq 0.23$
$T \approx 1.5 \cdot 10^7$ K
$\rho \approx 100$ g/cm³
Nuclear fusion
Corona
$1.01 \leq r/r_S \leq 20$
$T \approx 10^7$ K
$\rho \approx 10^{-15}$ g/cm³


Solar constant G_{sc}:
irradiance on top of the atmosphere
(= irradiance on a plane perpendicular to the rays,
at the distance of one AU)
AU (astronomical unit) = mean Sun-Earth distance
= 149.6 Mill. km
irradiance at the distance AU = radiant emittance of the Sun · Sun surface area / area of a sphere with the radius of one AU
radiation power of the Sun: $P_s = 4\pi r_s^2 \cdot \sigma \cdot (5777K)^4 = 3.85 \cdot 10^{26}$ W
$G_{sc} = P_s / 4\pi(AU)^2 \approx 1367$ W /m²

EXTRATERRESTRIAL RADIATION



VARIATION OF EXTRATERRESTRIAL RADIATION

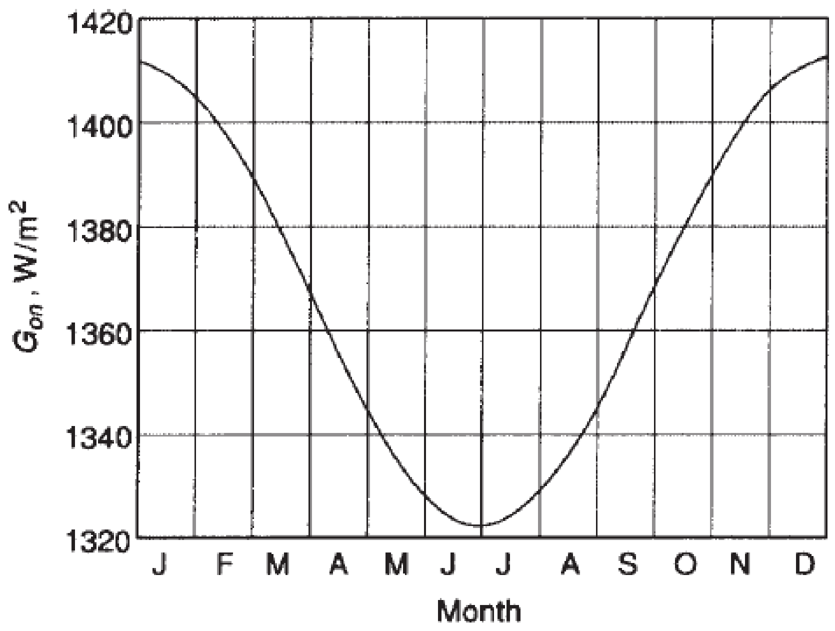


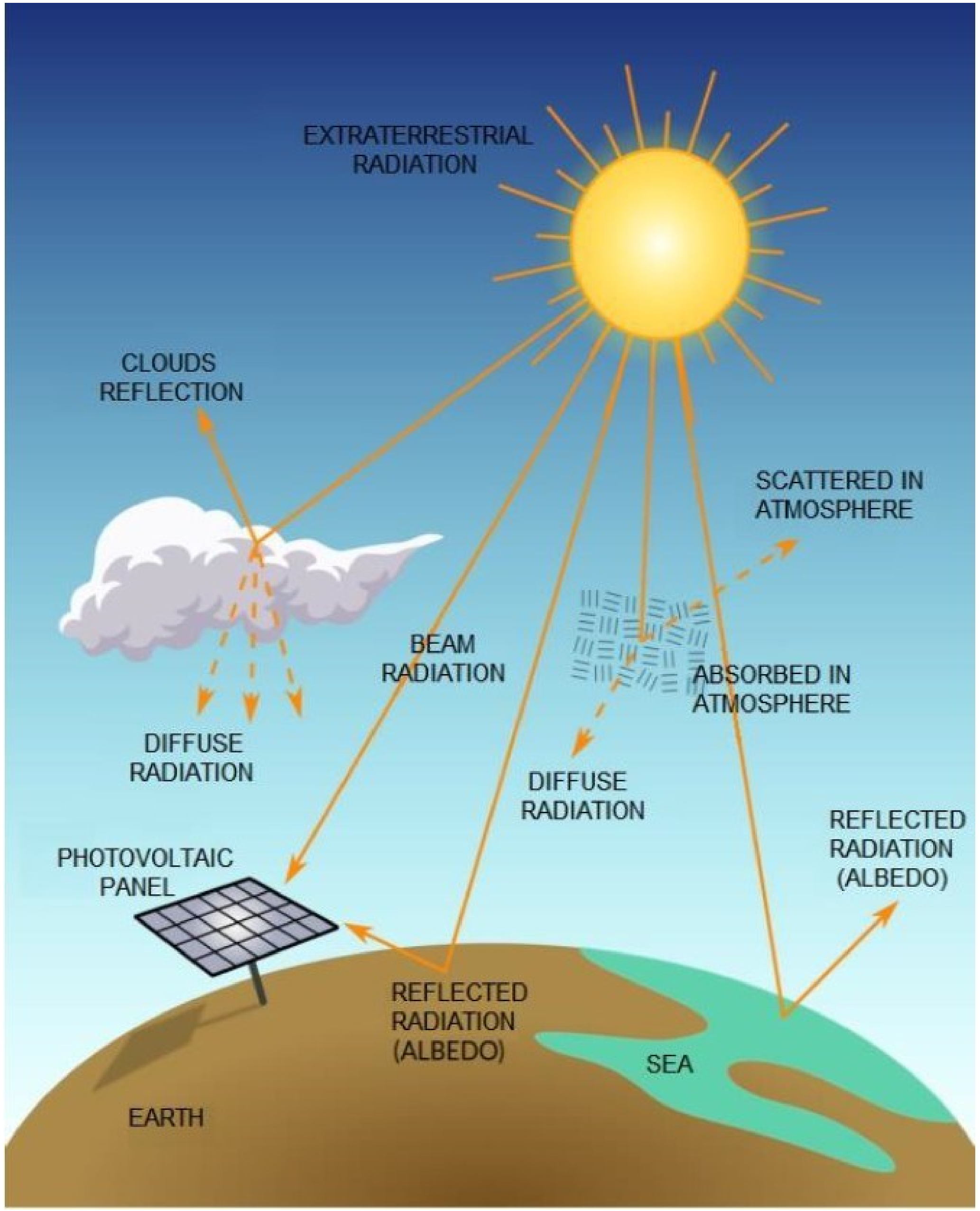
Figure 1.4.1 Variation of extraterrestrial solar radiation with time of year.

Two sources of variation in extraterrestrial radiation must be considered.

The first is the variation in the radiation emitted by the sun.

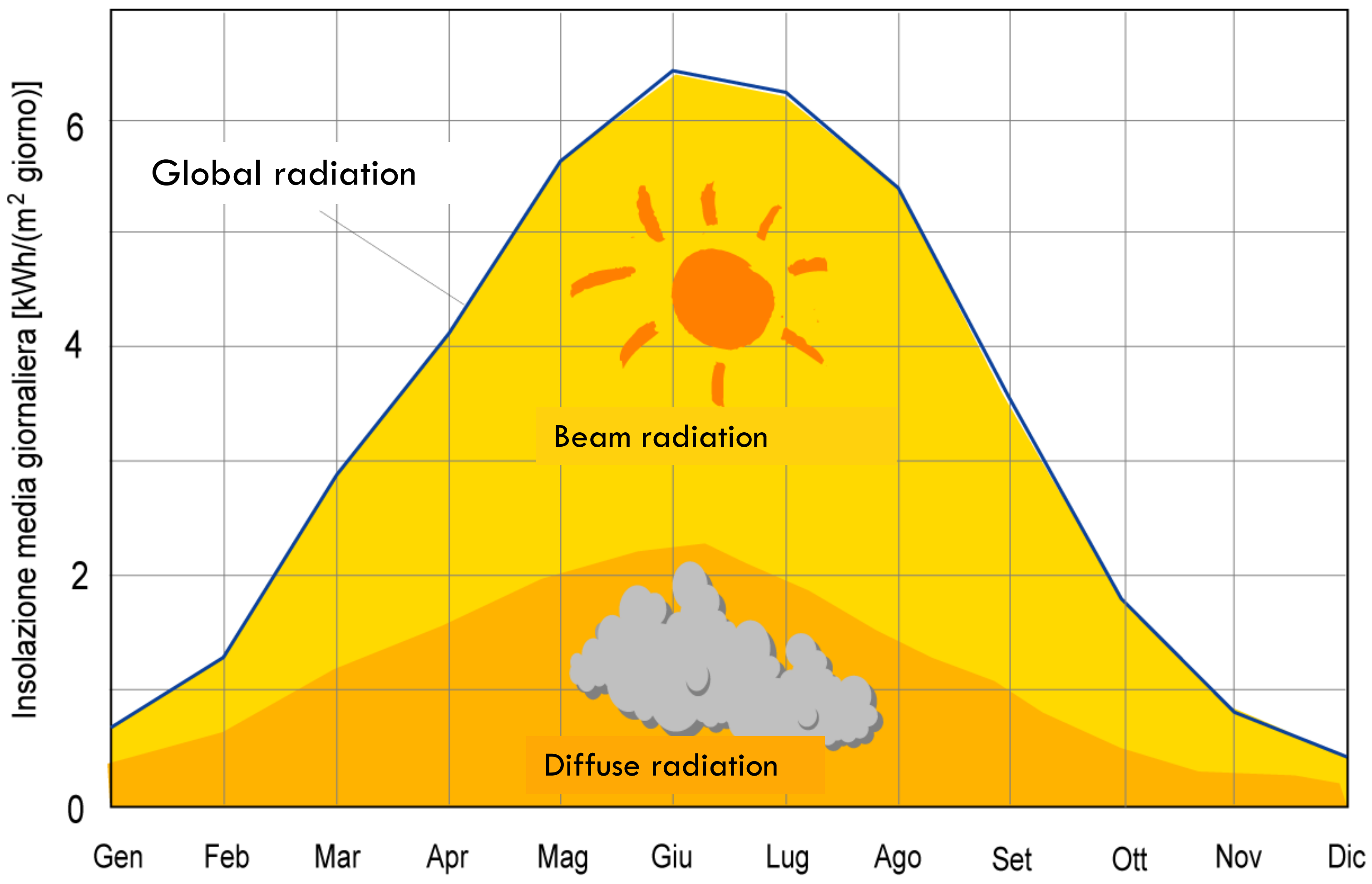
Variation of the earth-sun distance does lead to variation of extraterrestrial radiation flux in the range of ±3.3%.





EXTRATERRESTRIAL RADIATION
CLOUDS REFLECTION
SCATTERED IN ATMOSPHERE
BEAM RADIATION
ABSORBED IN ATMOSPHERE
DIFFUSE RADIATION
DIFFUSE RADIATION
REFLECTED RADIATION (ALBEDO)
PHOTOVOLTAIC PANEL
REFLECTED RADIATION (ALBEDO)
SEA
EARTH

BEAM AND DIFFUSE RADIATION ON HORIZONTAL SURFACES



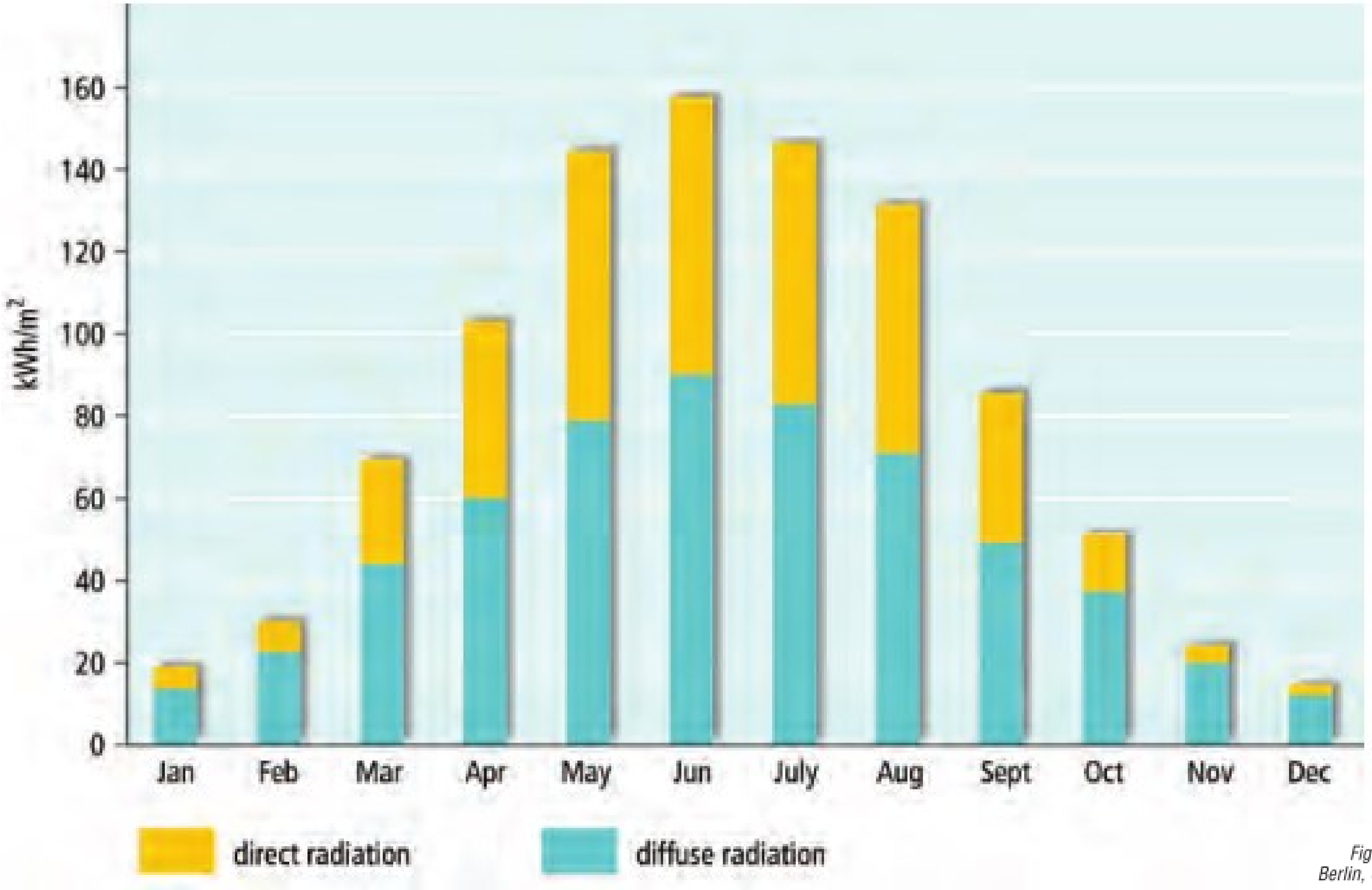
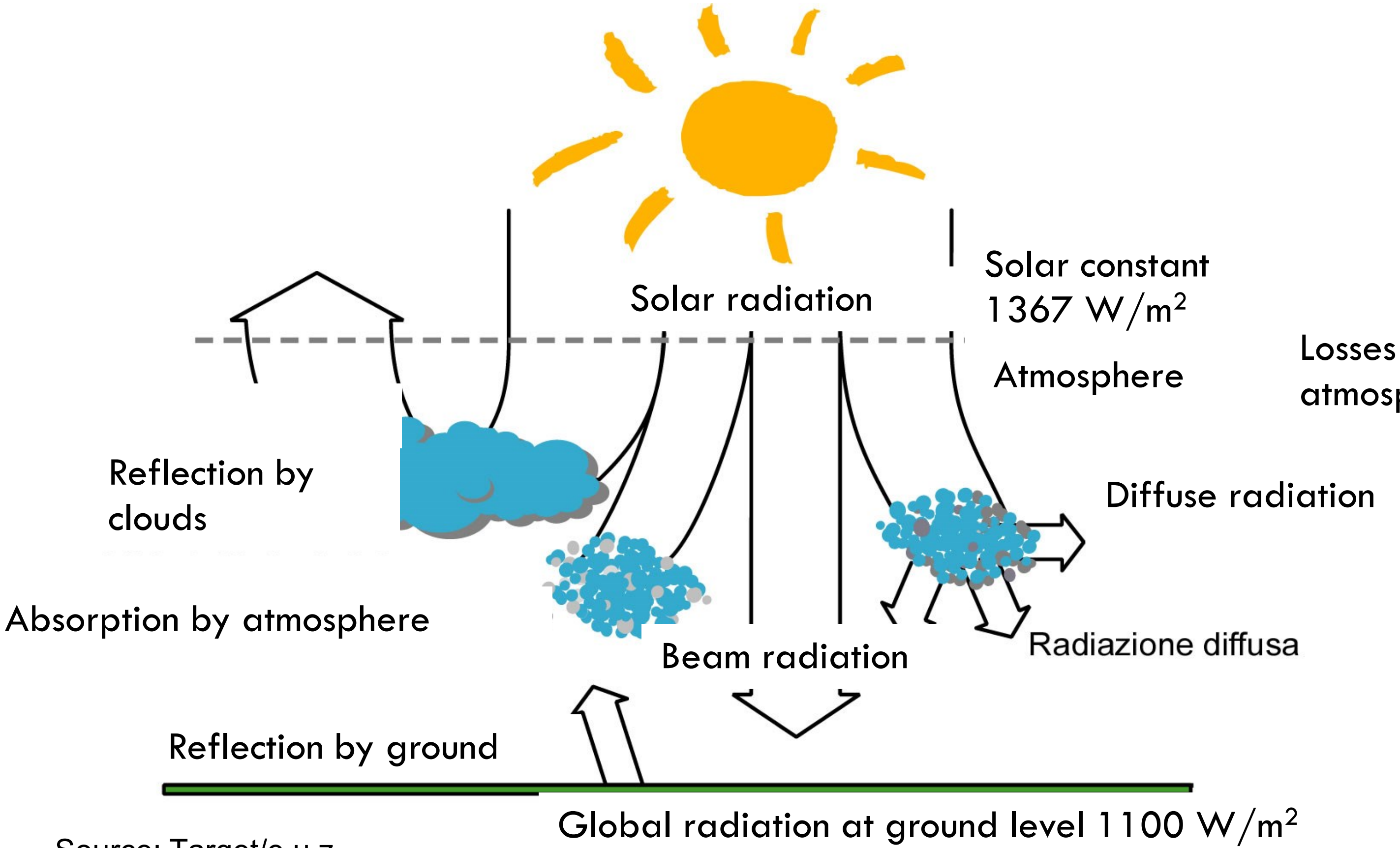
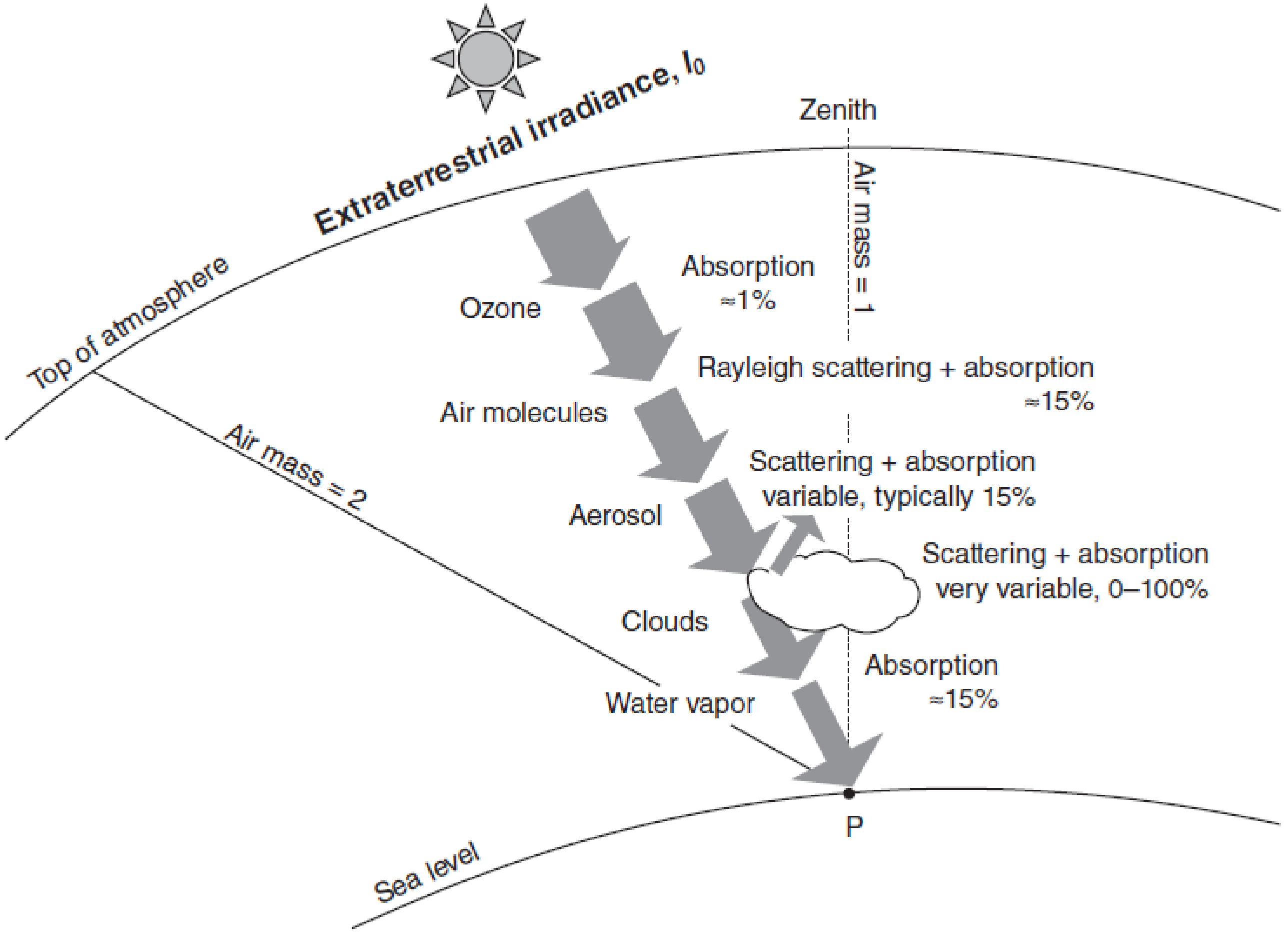


Figure 1.9a.
Berlin, Germany

SOLAR RADIATION AT GROUND LEVEL



Source: Target/e.u.z.



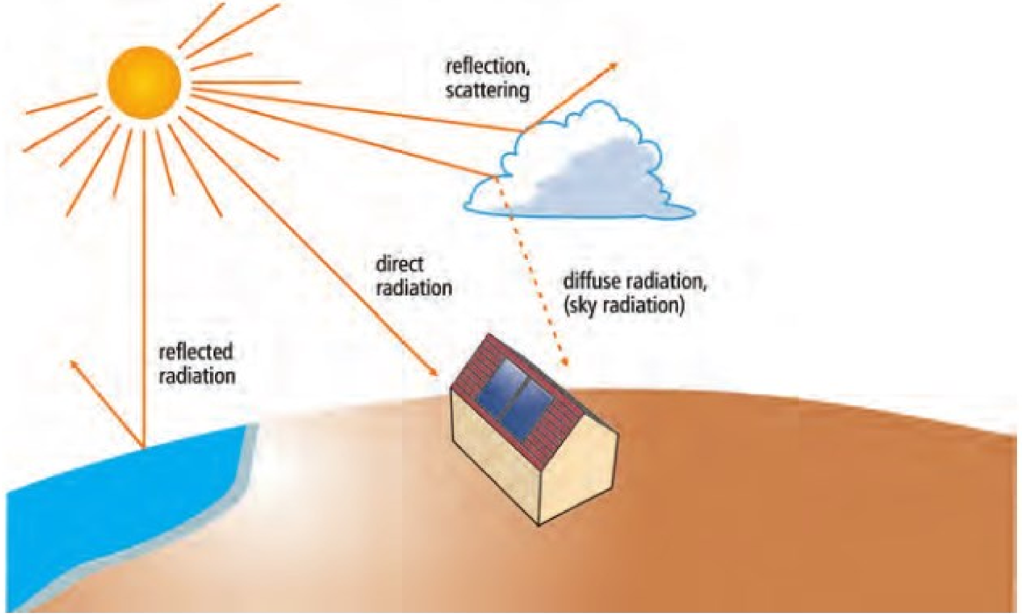
3.1 The main processes influencing solar radiation in the atmosphere and split into the major three components (global, direct, diffuse).

GLOBAL SOLAR IRRADIANCE AND ITS COMPONENTS

Global

Direct (Beam)

Diffused

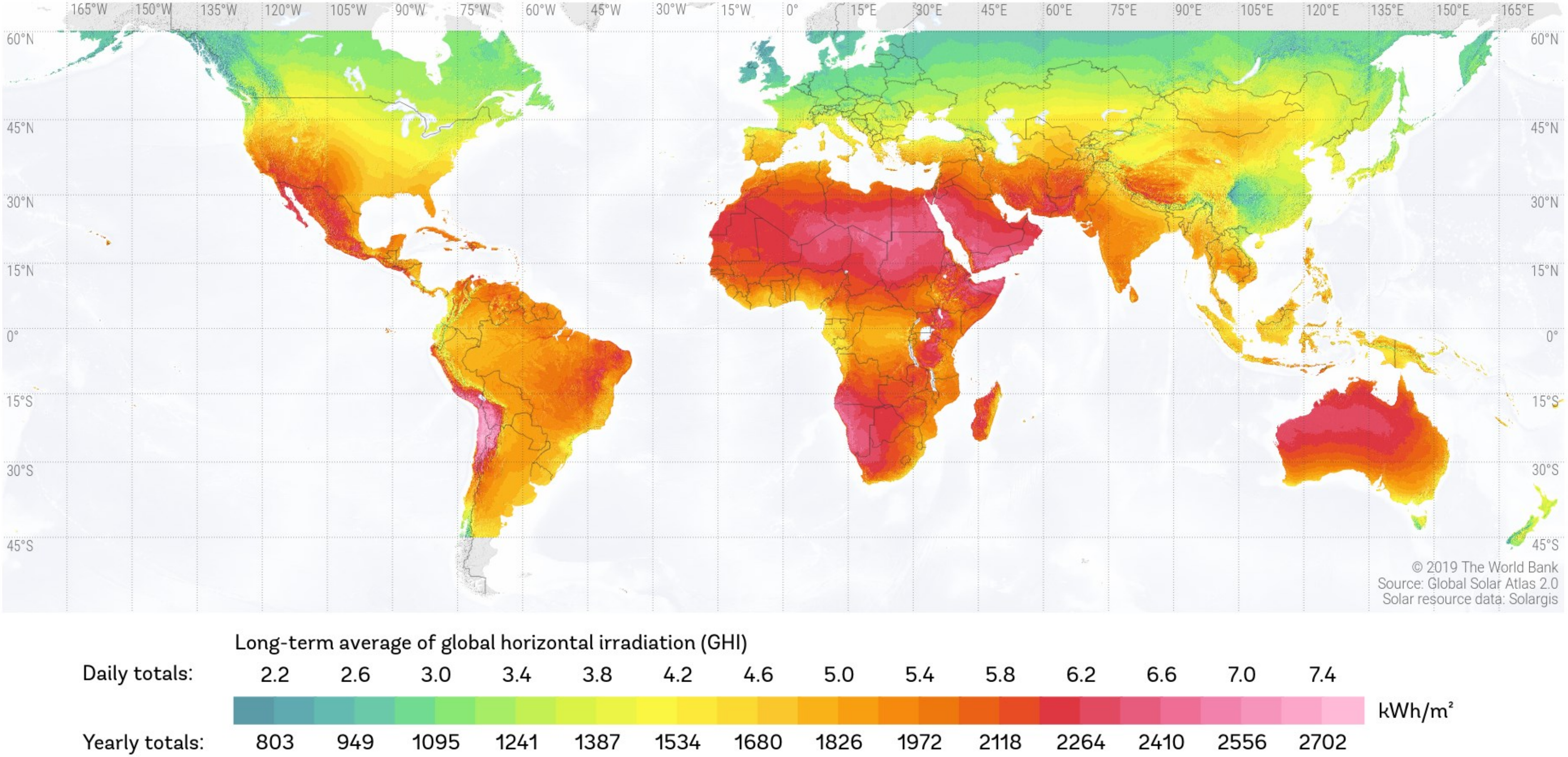


$$G_G = G_{dir} + G_{dif}$$

Even when the sky is clear and cloudless part of the sun's radiation comes from other directions and not just directly from the sun. This proportion of the radiation, which reaches the eye of the observer through the scattering of air molecules and dust particles, is known as *diffuse radiation*, G_{dif}. Part of this is also due to radiation reflected at the earth's surface. The radiation from the sun that meets the earth without any change in direction is called *direct radiation*, G_{dir}. The sum of direct and diffuse radiation is known as *global solar irradiance*, G_G (Figure 1.5).

SOLAR RESOURCE MAP

GLOBAL HORIZONTAL IRRADIATION



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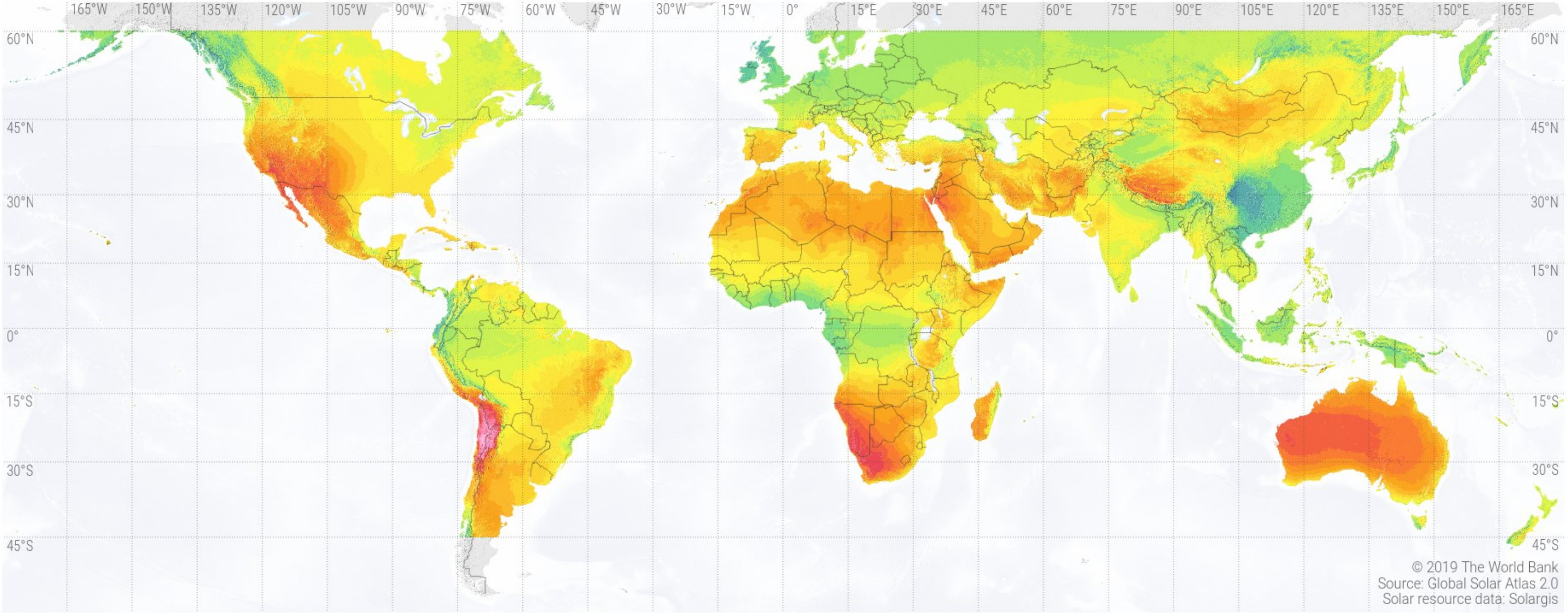
SOLAR RESOURCE MAP

DIRECT NORMAL IRRADIATION

WORLD BANK GROUP ESMAP SOLARGIS



Long-term average of direct normal irradiation (DNI)

Daily totals:	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0
Yearly totals:	365	730	1095	1461	1826	2191	2556	2922	3287	3652

kWh/m²

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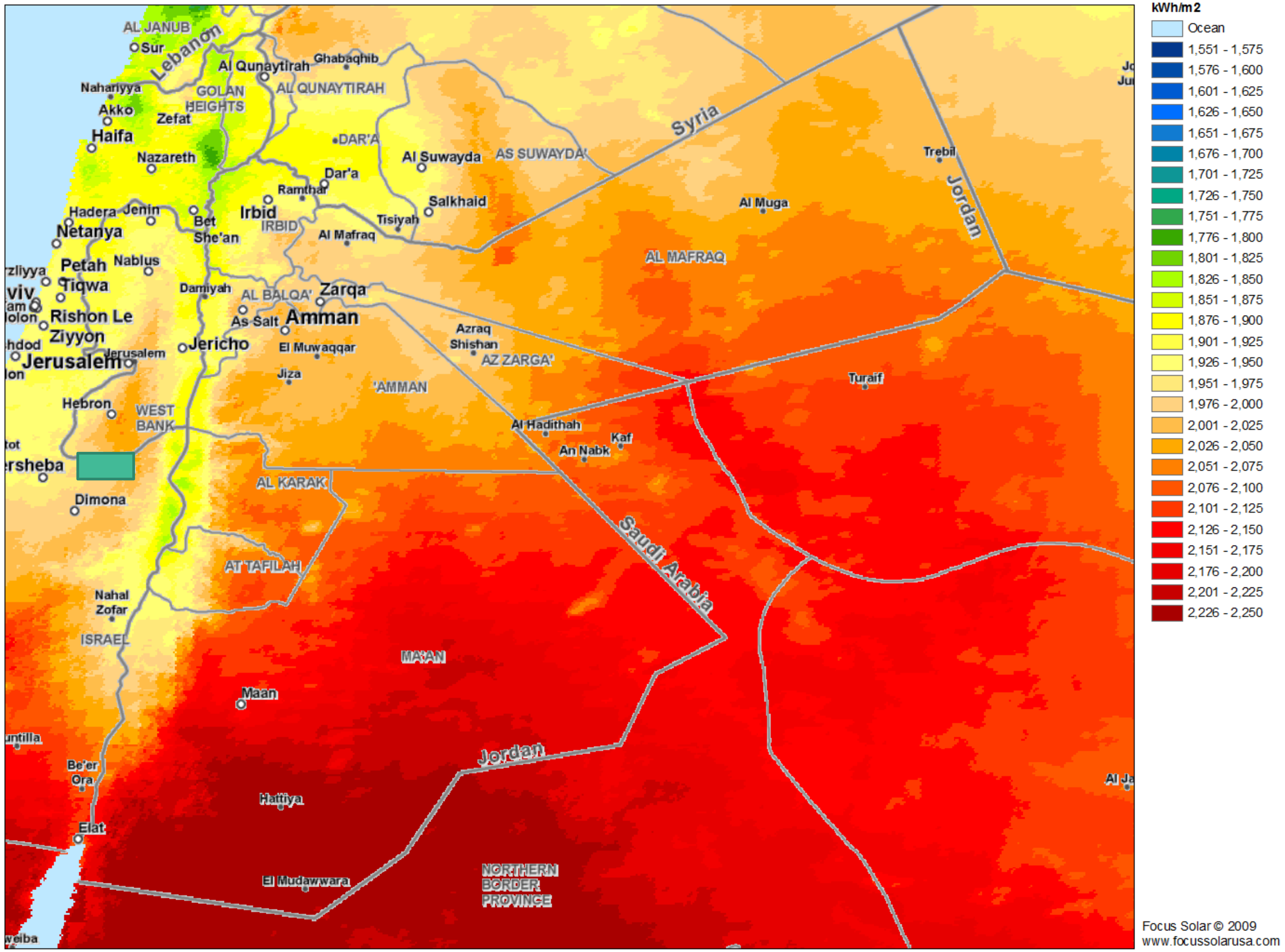
Solar Radiation Jordan



WHY THERE IS A DIFFERENCE IN THE SOLAR RADIATION BETWEEN DIFFERENT LOCATIONS ?

1. SUN PATH

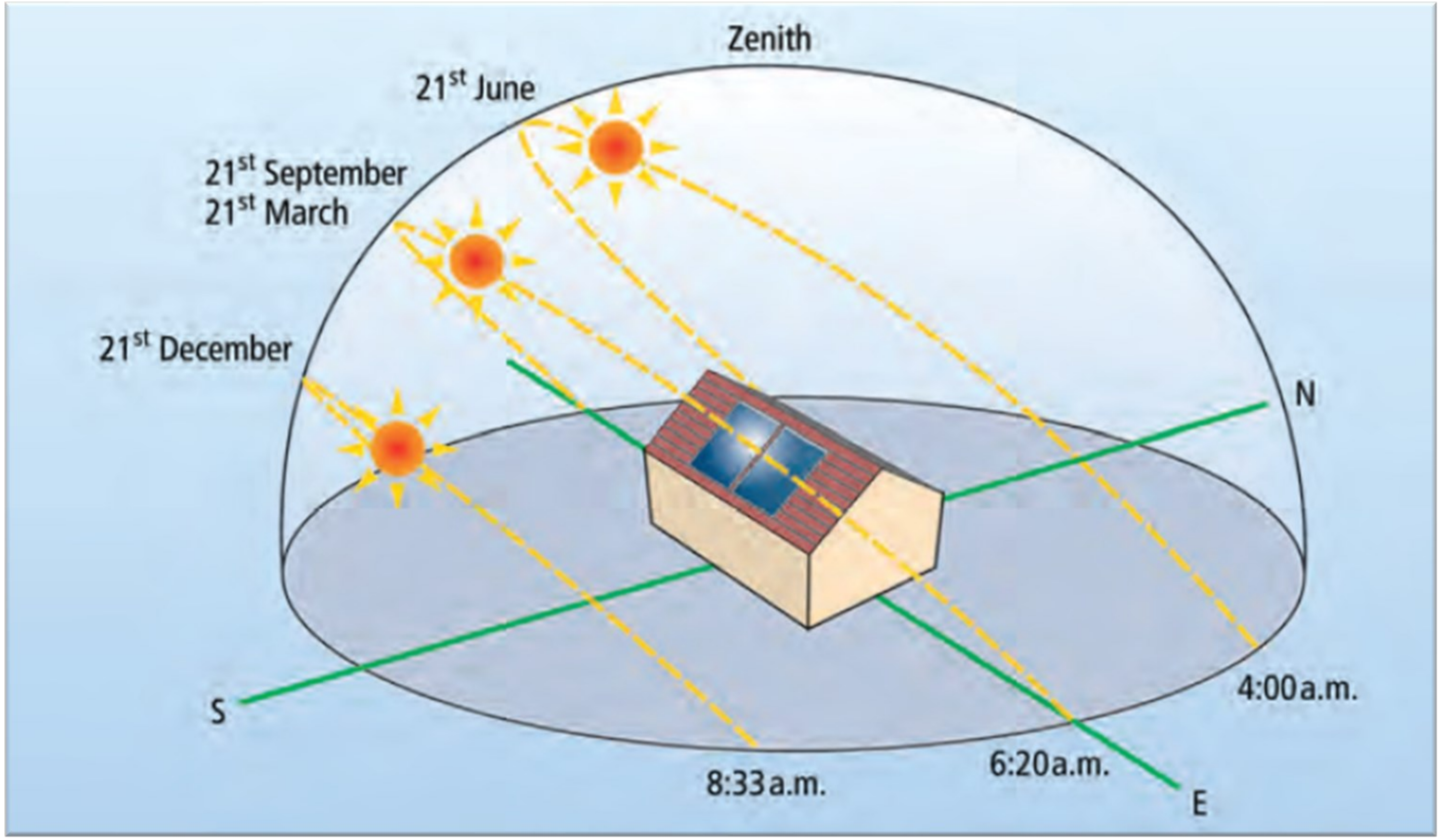
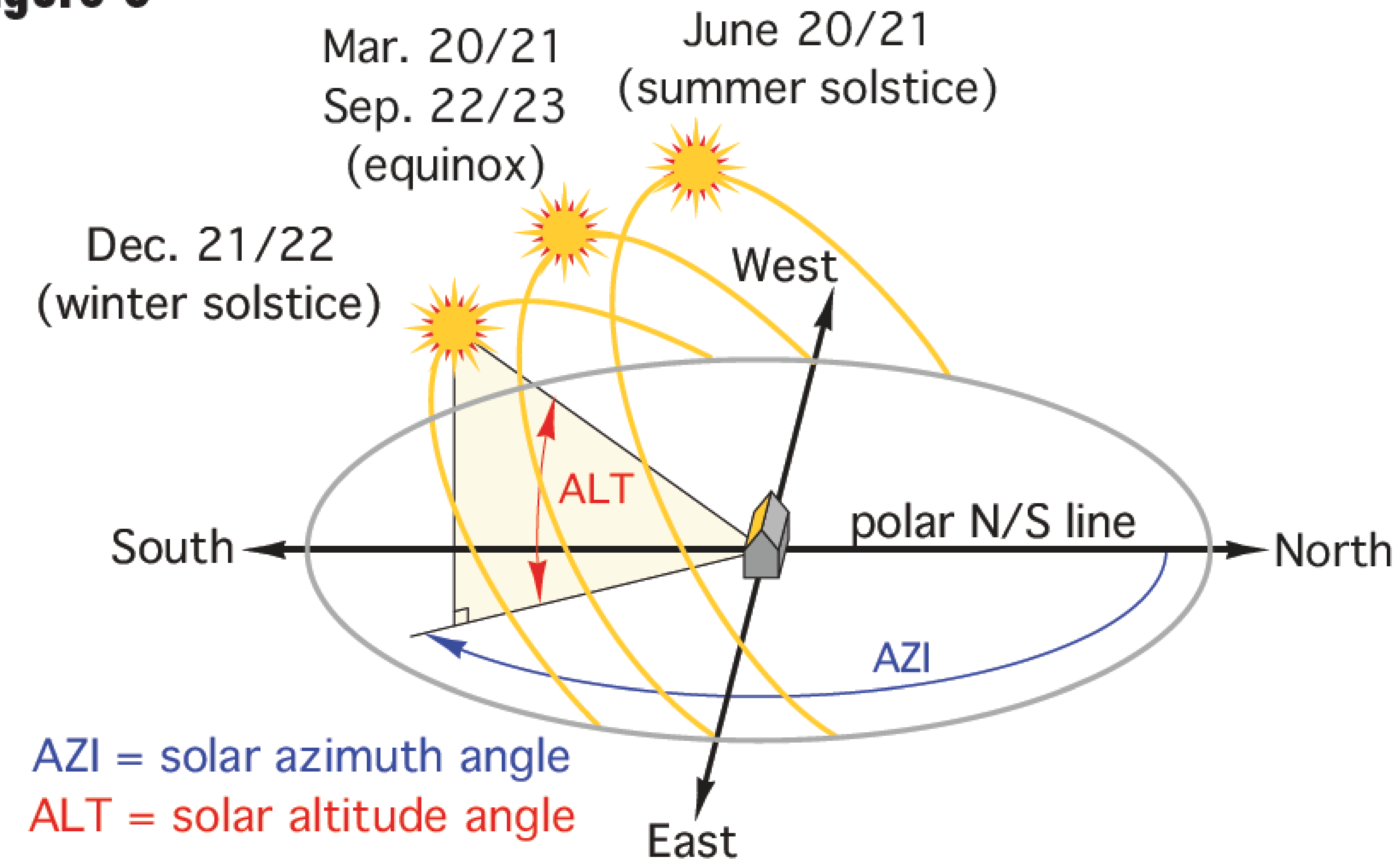
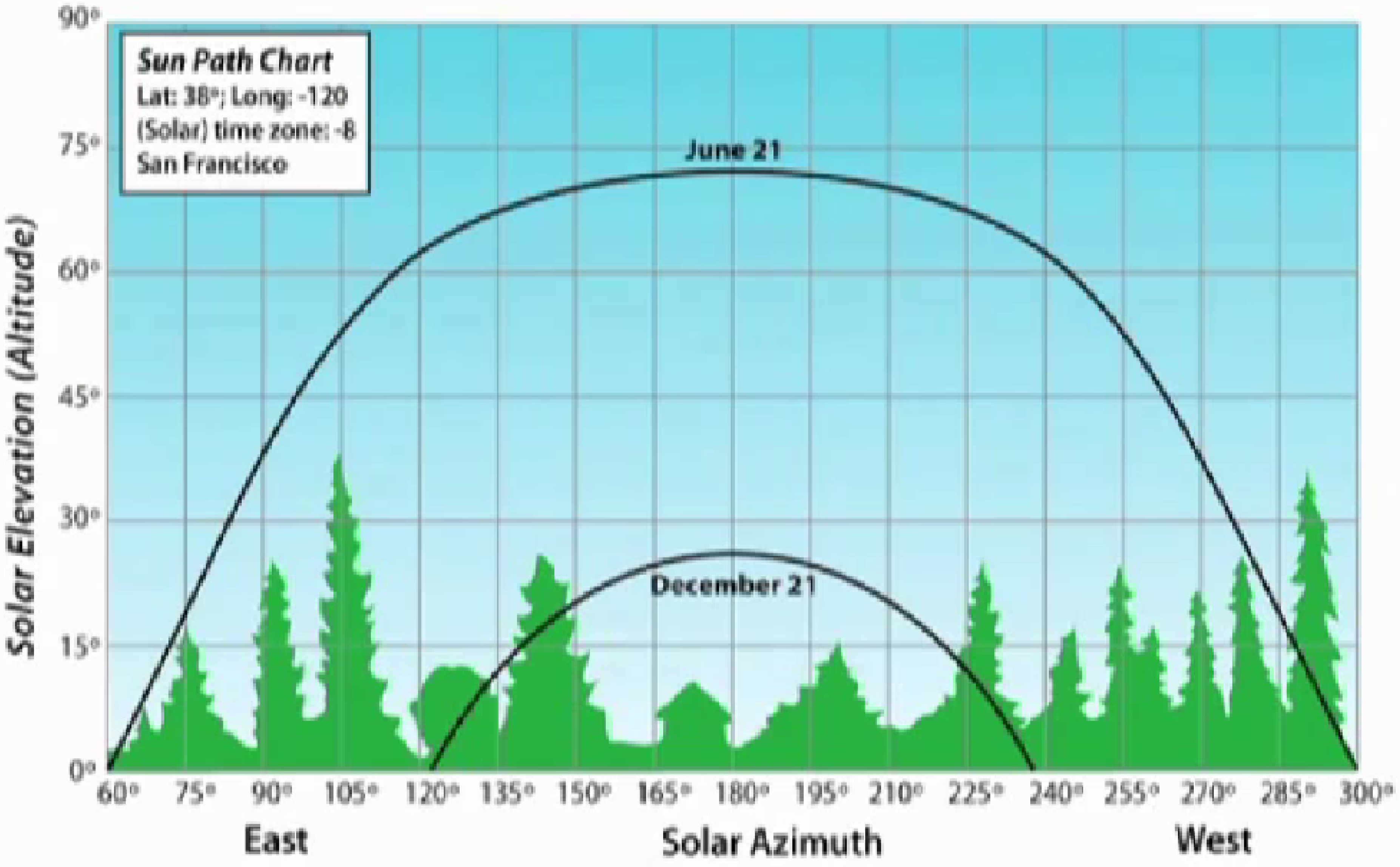
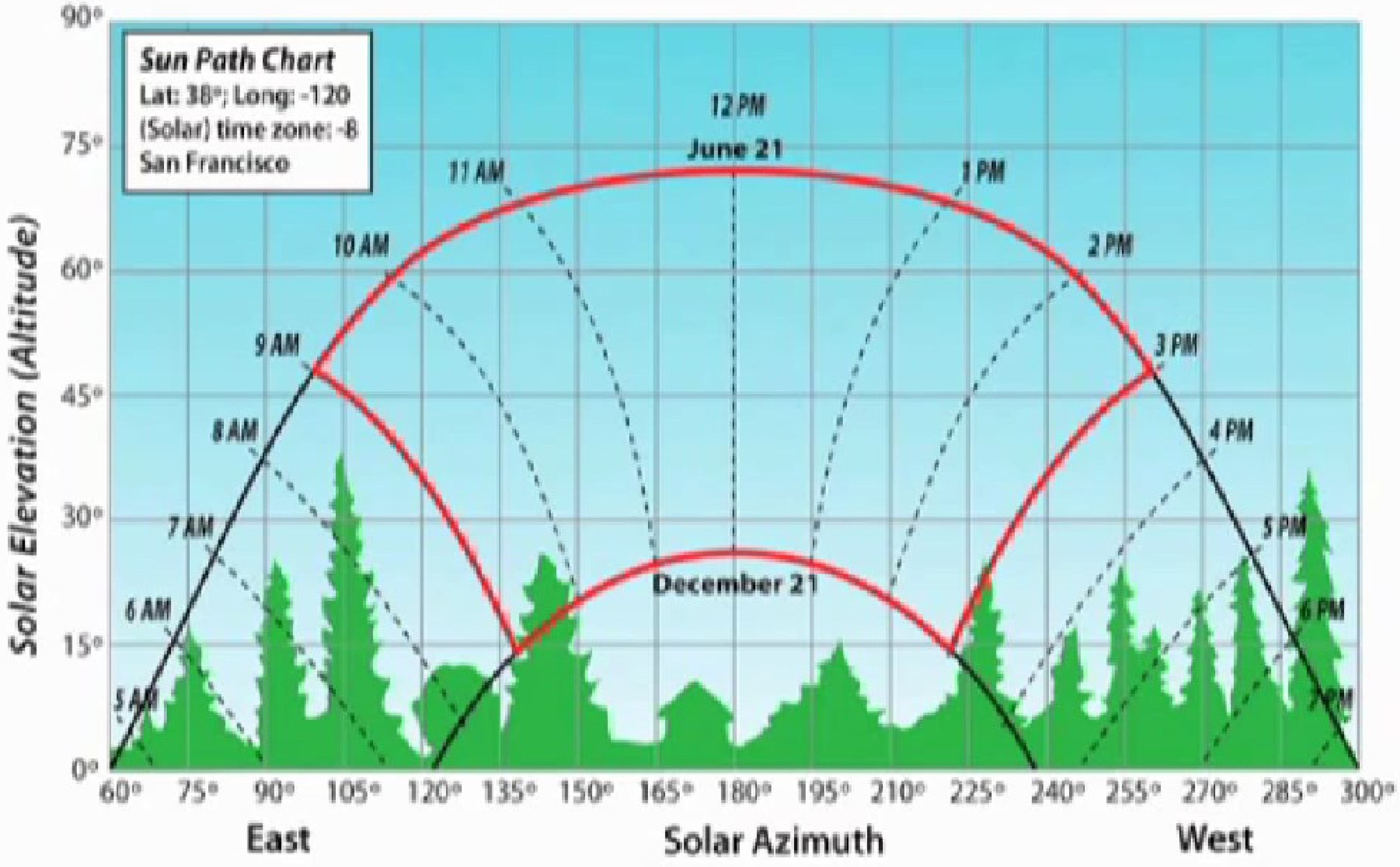

Zenith
21st June
21st September
21st March
21st December
N
S
E
4:00 a.m.
6:20 a.m.
8:33 a.m.

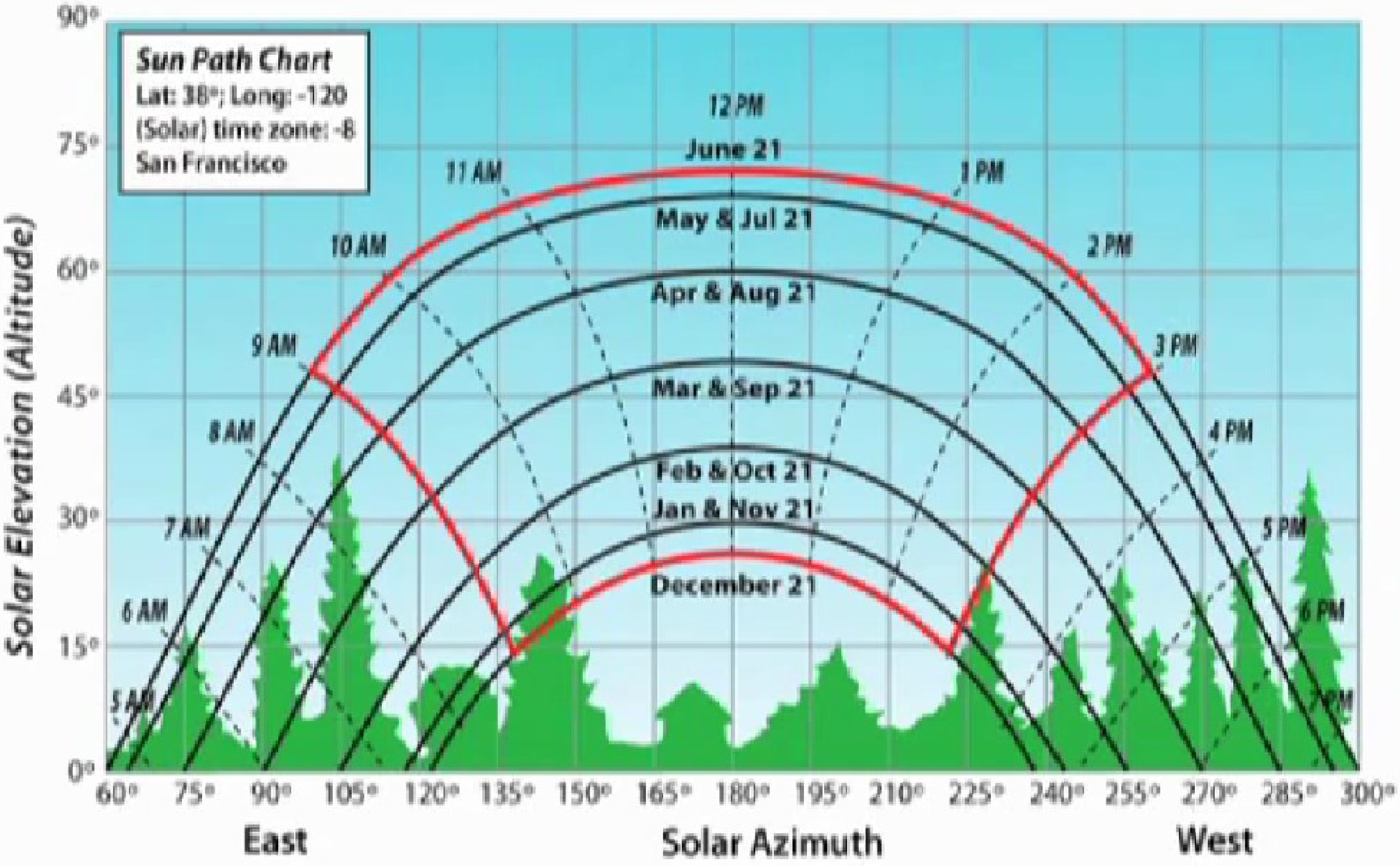
Figure 6


Mar. 20/21
Sep. 22/23
(equinox)
June 20/21
(summer solstice)
Dec. 21/22
(winter solstice)
West
ALT
South
polar N/S line
North
AZI
East
AZI = solar azimuth angle
ALT = solar altitude angle



Sun Path Chart
Lat: 38°; Long: -120
(Solar) time zone: -8
San Francisco
June 21
December 21
Solar Elevation (Altitude)
90°
75°
60°
45°
30°
15°
0°
60°
75°
90°
105°
120°
135°
150°
165°
180°
195°
210°
225°
240°
255°
270°
285°
300°
East
Solar Azimuth
West


Sun Path Chart
Lat: 38°; Long: -120
(Solar) time zone: -8
San Francisco
12 PM
June 21
11 AM
1 PM
10 AM
2 PM
9 AM
3 PM
8 AM
4 PM
7 AM
5 PM
6 AM
6 PM
5 AM
7 PM
December 21
Solar Elevation (Altitude)
90°
75°
60°
45°
30°
15°
0°
60°
75°
90°
105°
120°
135°
150°
165°
180°
195°
210°
225°
240°
255°
270°
285°
300°
East
Solar Azimuth
West


Sun Path Chart
Lat: 38°; Long: -120
(Solar) time zone: -8
San Francisco
12 PM
June 21
May & Jul 21
Apr & Aug 21
Mar & Sep 21
Feb & Oct 21
Jan & Nov 21
December 21
11 AM
10 AM
9 AM
8 AM
7 AM
6 AM
5 AM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
7 PM
90°
75°
60°
45°
30°
15°
0°
Solar Elevation (Altitude)
60° 75° 90° 105° 120° 135° 150° 165° 180° 195° 210° 225° 240° 255° 270° 285° 300°
East
Solar Azimuth
West

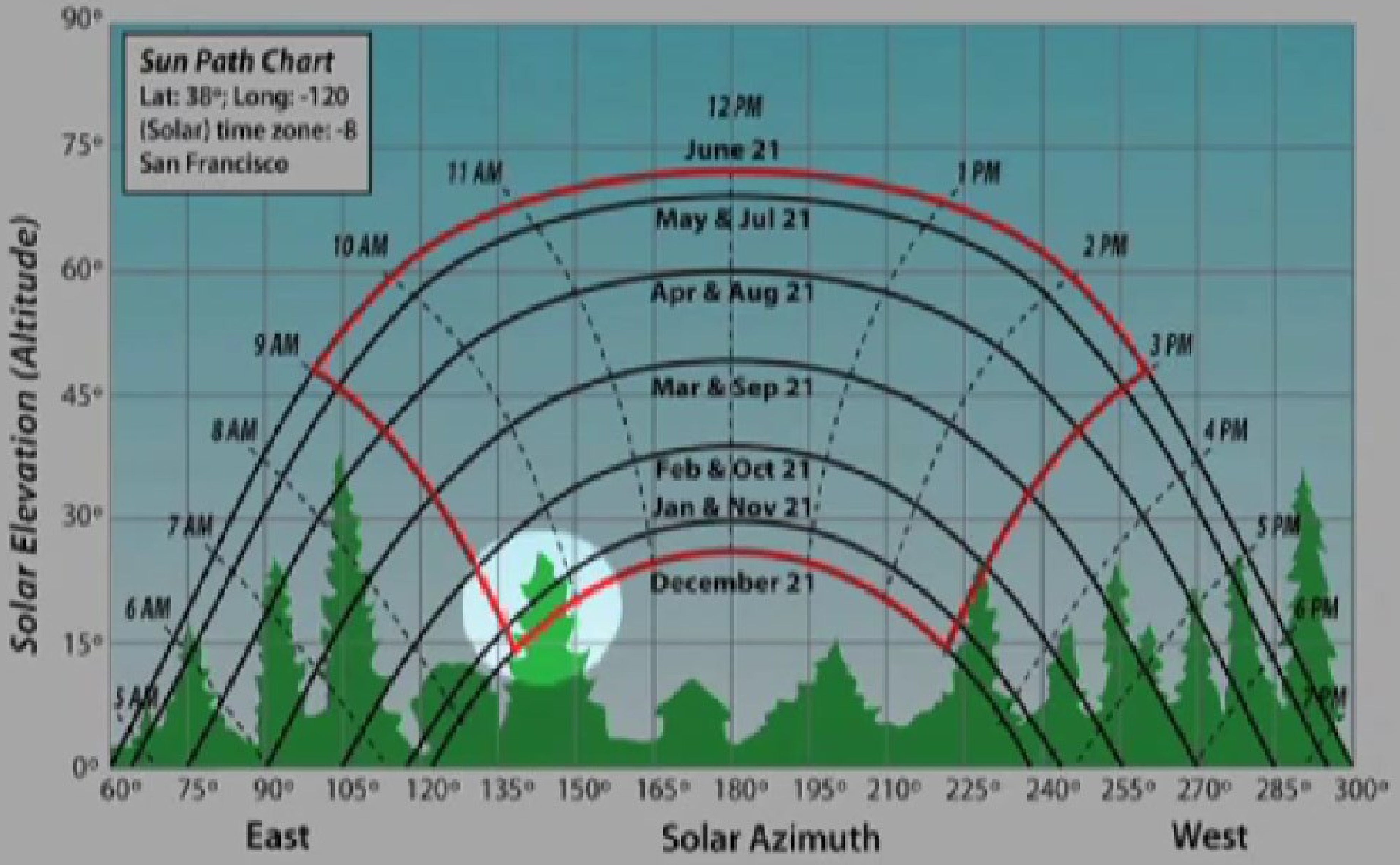
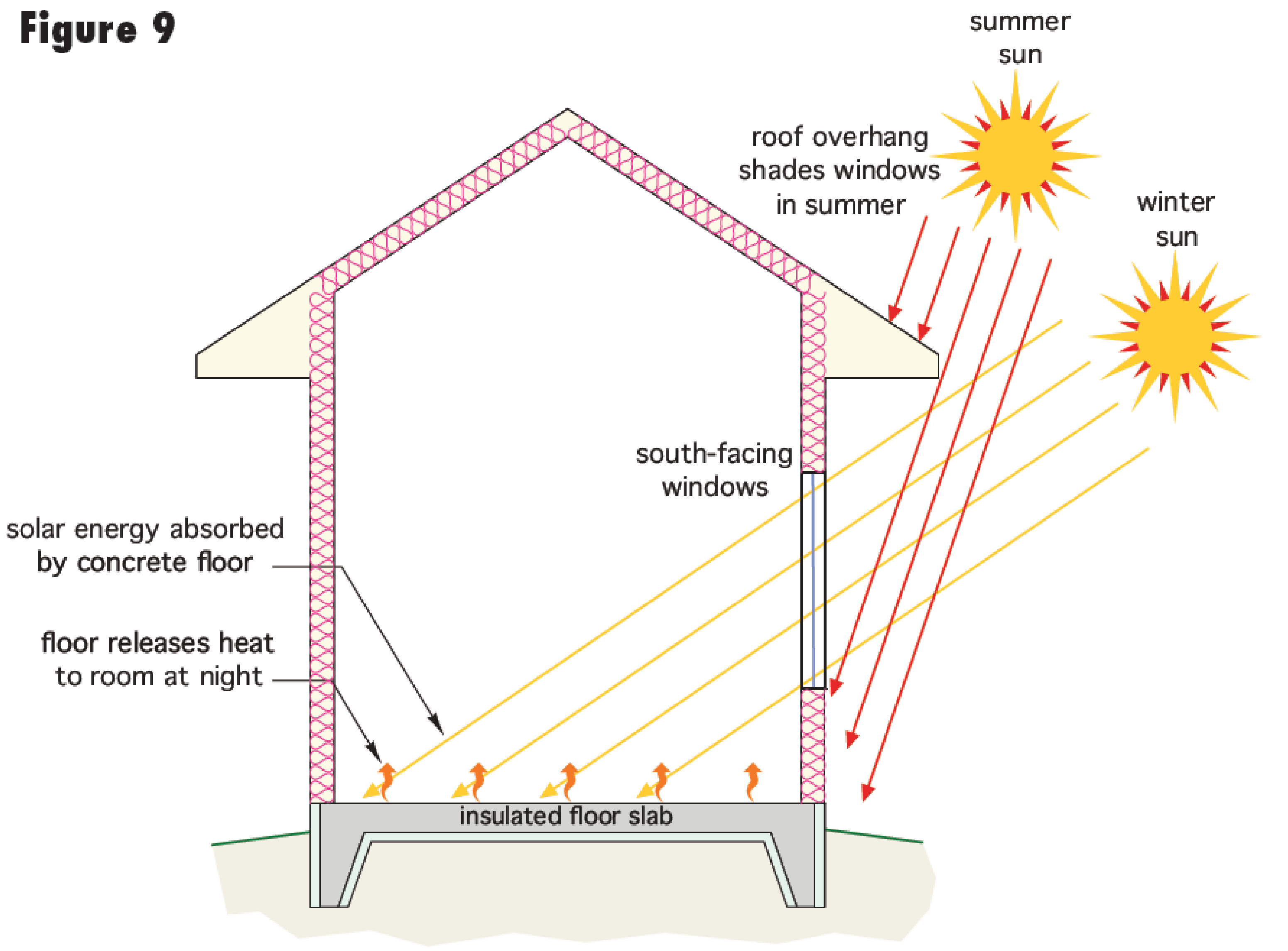
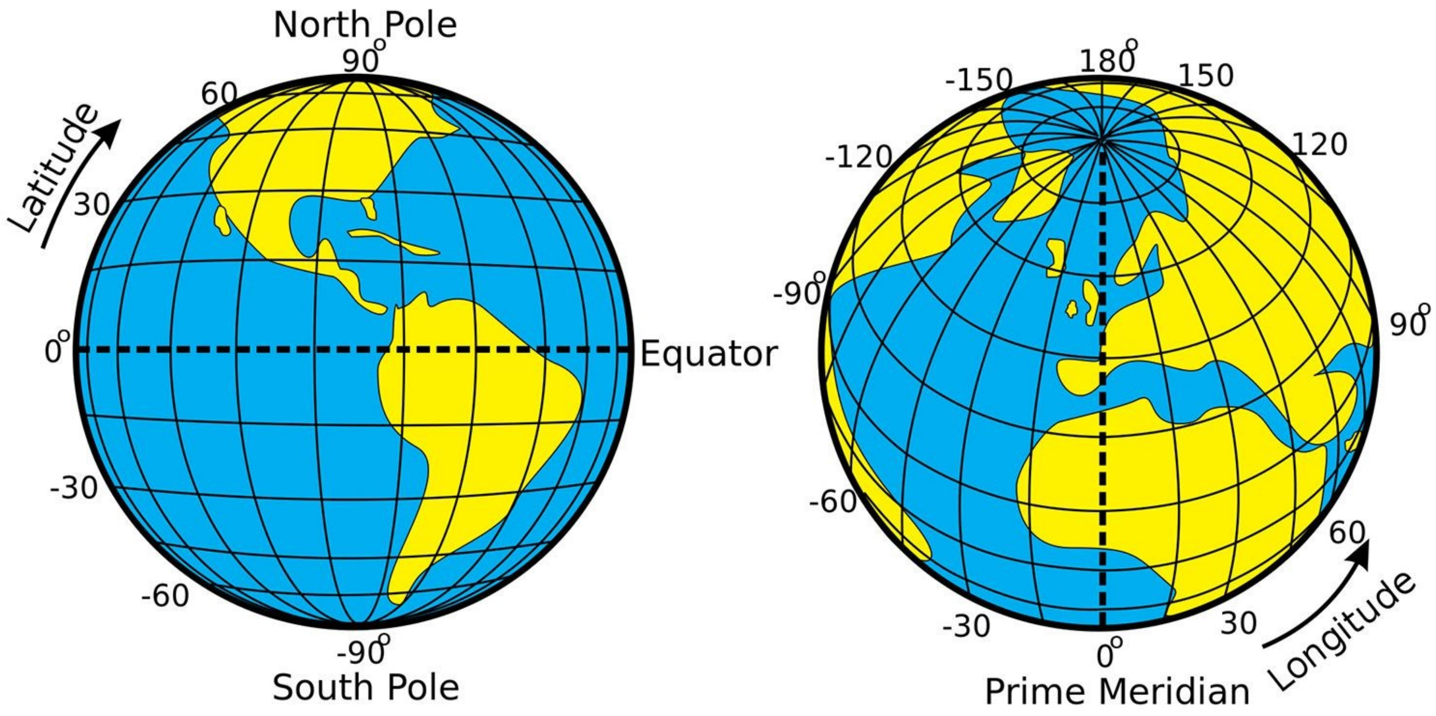

Sun Path Chart
Lat: 38°; Long: -120
(Solar) time zone: -8
San Francisco
12 PM
June 21
May & Jul 21
Apr & Aug 21
Mar & Sep 21
Feb & Oct 21
Jan & Nov 21
December 21
5 AM
6 AM
7 AM
8 AM
9 AM
10 AM
11 AM
1 PM
2 PM
3 PM
4 PM
5 PM
6 PM
7 PM
Solar Elevation (Altitude)
0°
15°
30°
45°
60°
75°
90°
60°
75°
90°
105°
120°
135°
150°
165°
180°
195°
210°
225°
240°
255°
270°
285°
300°
East
Solar Azimuth
West

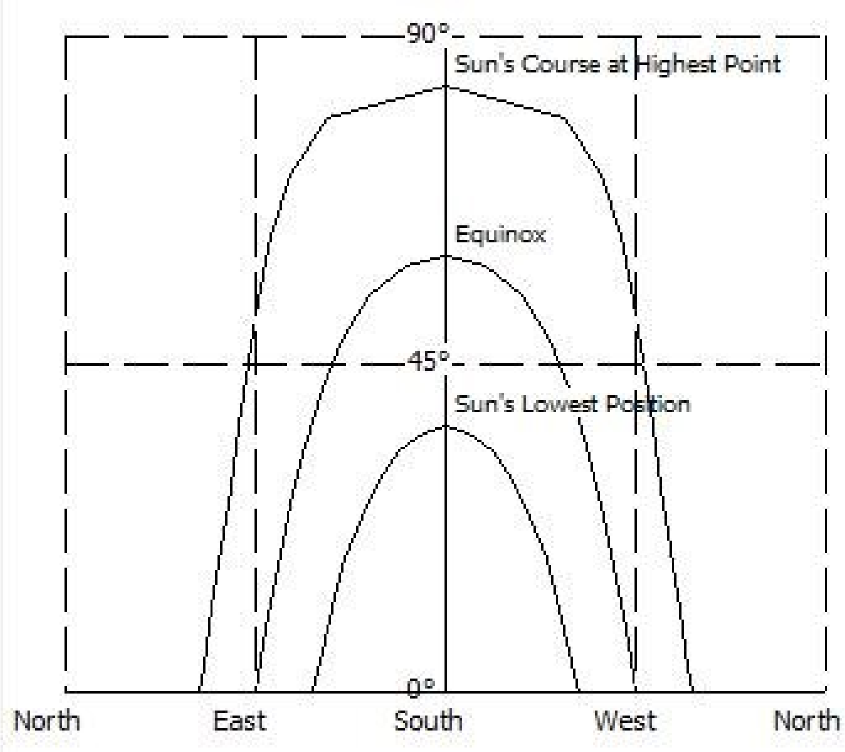
Figure 9


summer sun
roof overhang shades windows in summer
winter sun
south-facing windows
solar energy absorbed by concrete floor
floor releases heat to room at night
insulated floor slab

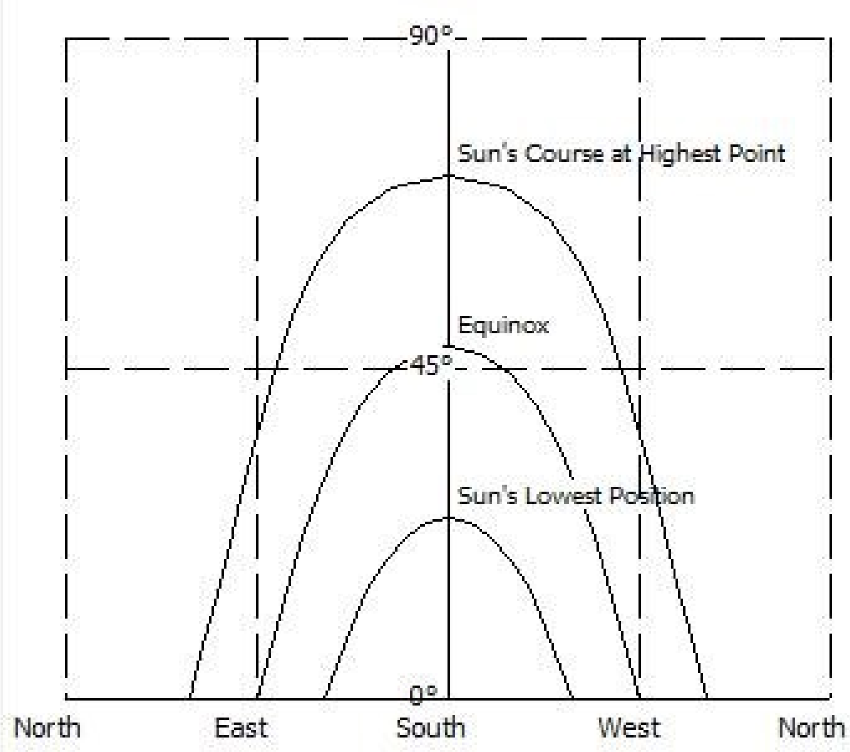
2. GEOGRAPHICAL LOCATION



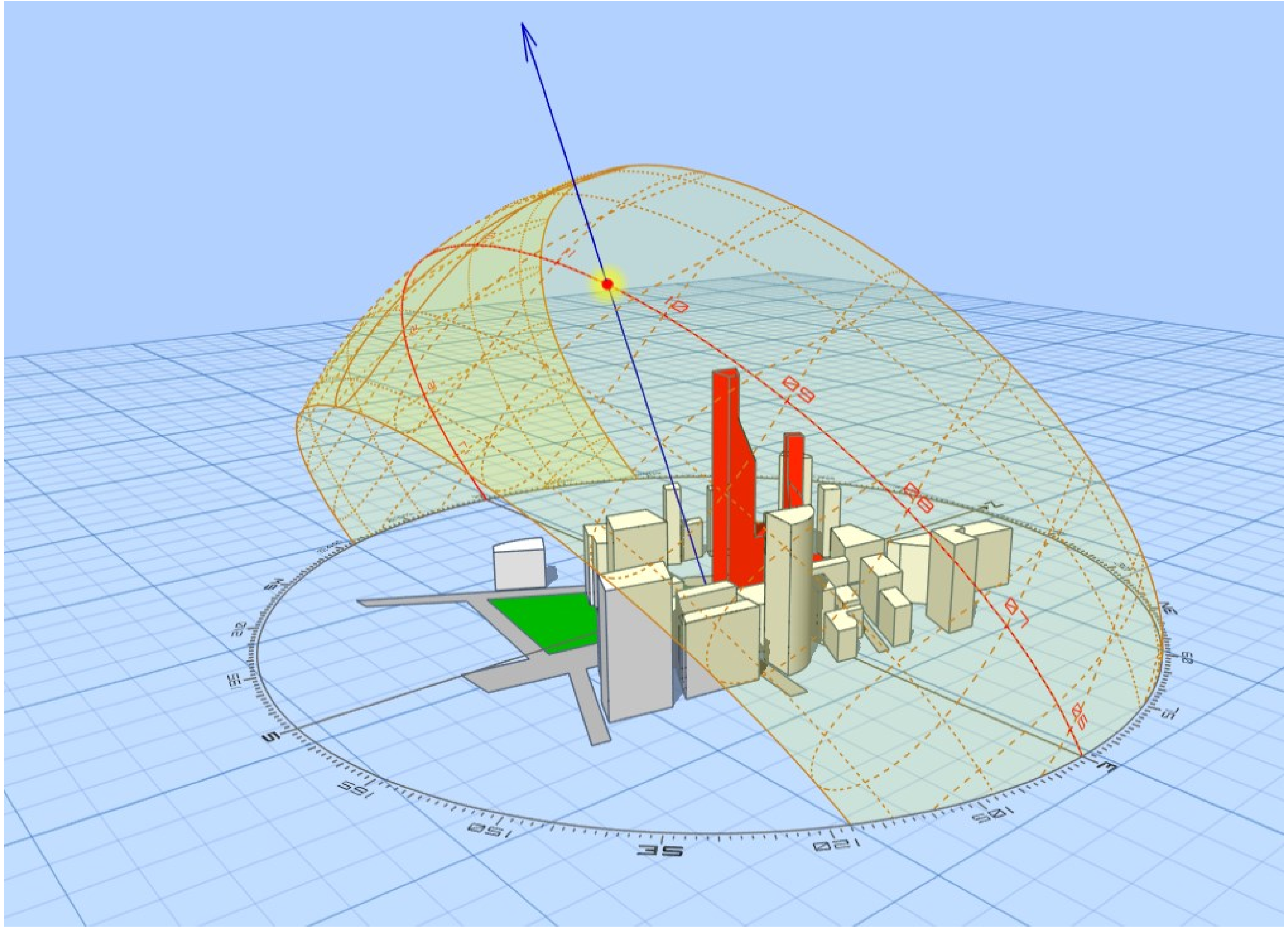
SUN TRAJECTORY IN CAIRO AND ROME



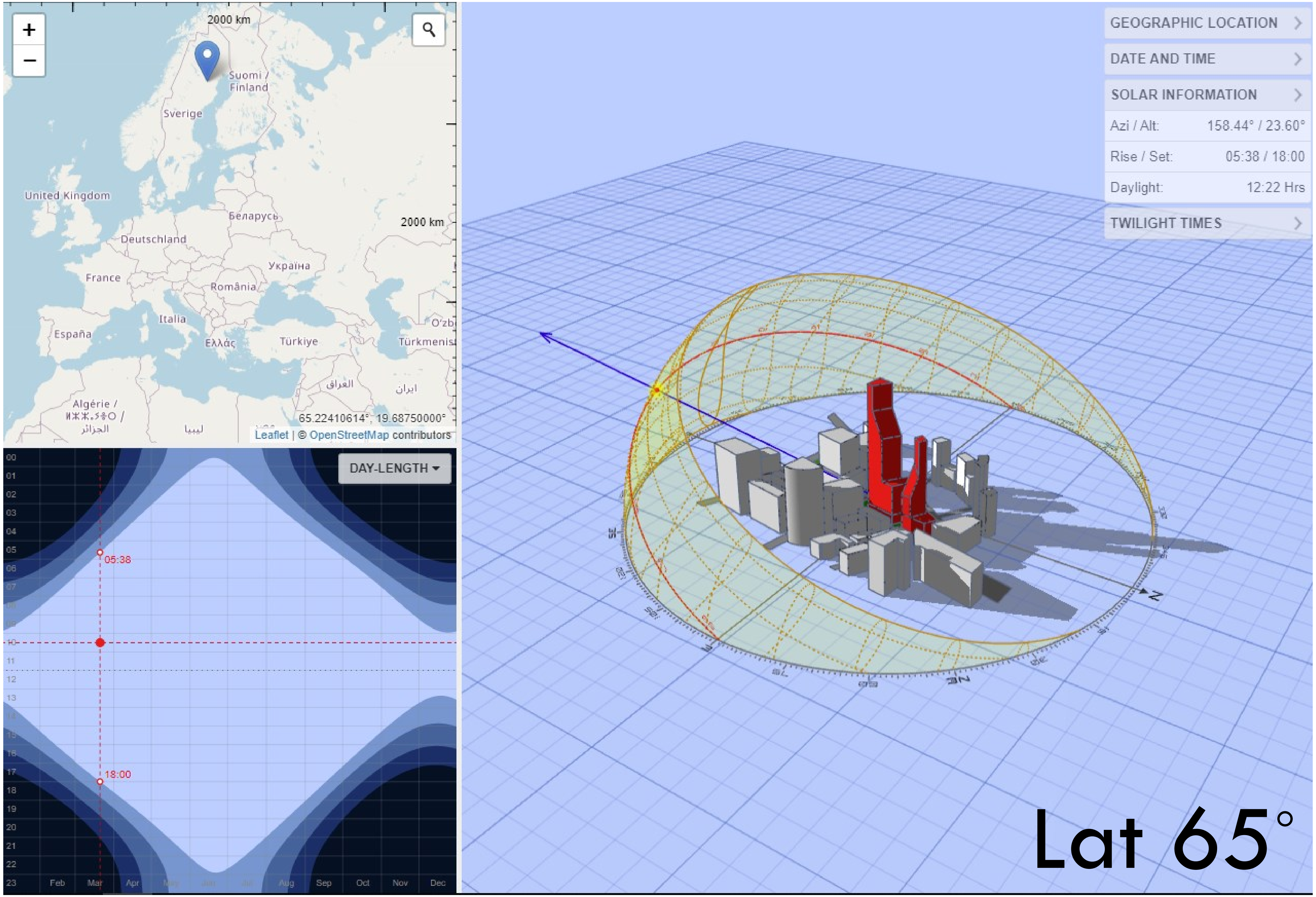
Cairo



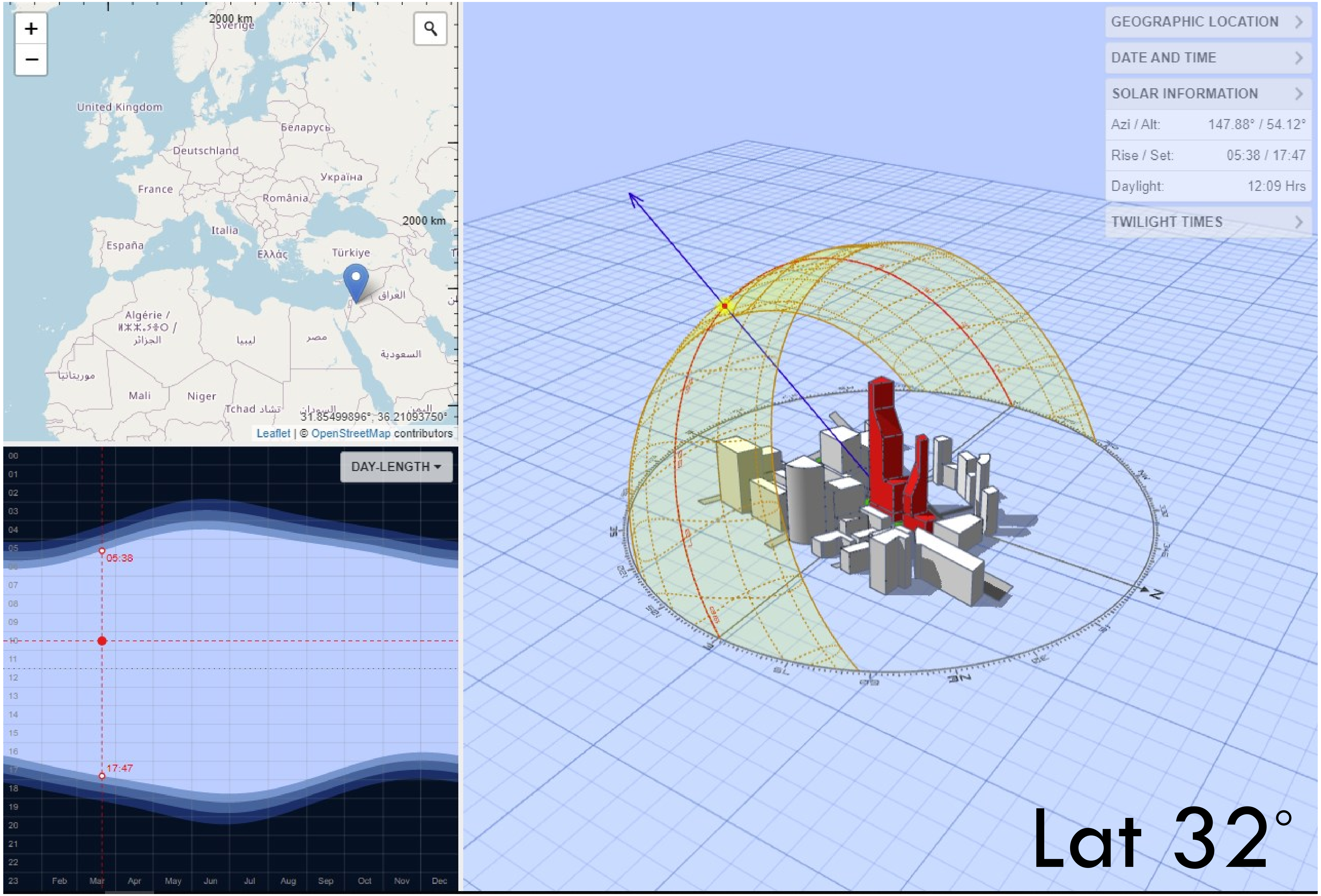
Rome



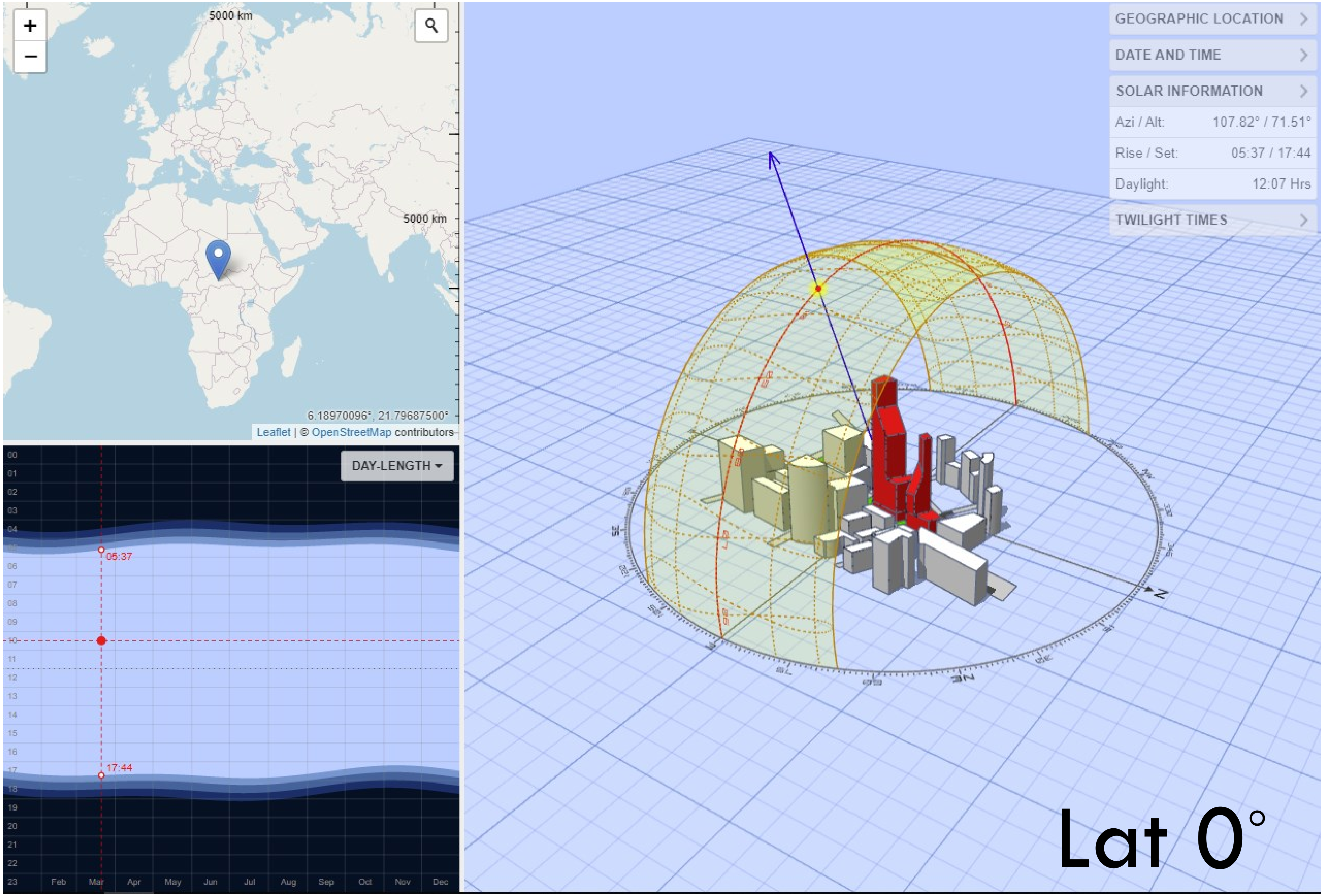
http://andrewmarsh.com/apps/staging/sunpath3d.html


2000 km
Suomi / Finland
Sverige
United Kingdom
Беларусь
2000 km
Deutschland
Україна
France
România
Italia
España
Ελλάς
Türkiye
Türkmenis
العراق
ایران
Algérie /
الجزائر
ليبيا
65.22410614°, 19.68750000°
Leaflet | © OpenStreetMap contributors
DAY-LENGTH
05:38
18:00
Feb
Mar
Apr
Sep
Oct
Nov
Dec
GEOGRAPHIC LOCATION
DATE AND TIME
SOLAR INFORMATION
Azi / Alt: 158.44° / 23.60°
Rise / Set: 05:38 / 18:00
Daylight: 12:22 Hrs
TWILIGHT TIMES

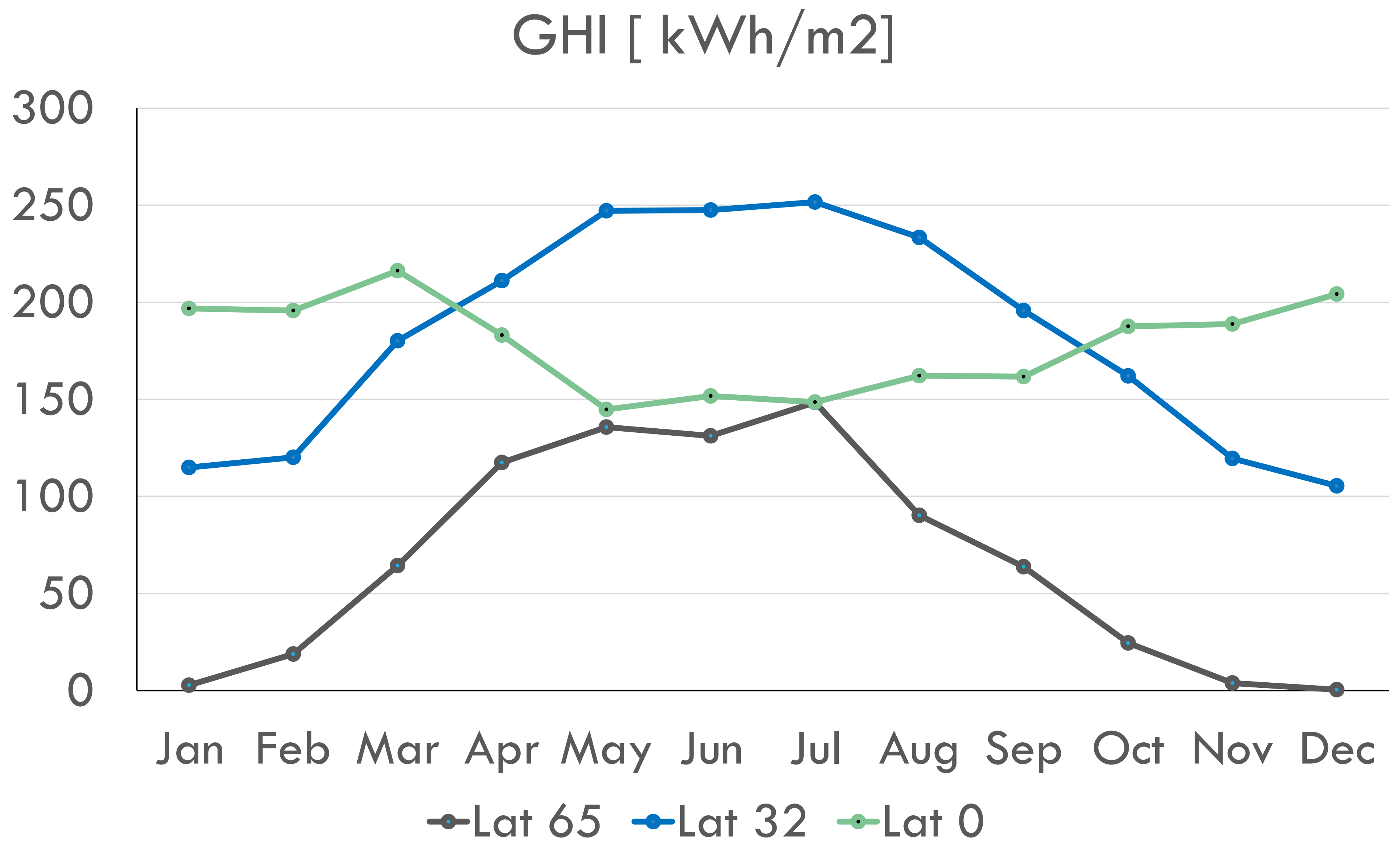
Lat 65°


GEOGRAPHIC LOCATION
DATE AND TIME
SOLAR INFORMATION
Azi / Alt: 147.88° / 54.12°
Rise / Set: 05:38 / 17:47
Daylight: 12:09 Hrs
TWILIGHT TIMES
DAY-LENGTH
05:38
17:47
31.85499896°, 36.21093750°
Leaflet | © OpenStreetMap contributors
United Kingdom
Deutschland
France
España
Italia
Türkiye
Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Lat 32°


5000 km
5000 km
6.18970096°, 21.79687500°
Leaflet | © OpenStreetMap contributors
DAY-LENGTH
05:37
17:44
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
GEOGRAPHIC LOCATION
DATE AND TIME
SOLAR INFORMATION
Azi / Alt: 107.82° / 71.51°
Rise / Set: 05:37 / 17:44
Daylight: 12:07 Hrs
TWILIGHT TIMES

Lat 0°


GHI [kWh/m2]
300
250
200
150
100
50
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Lat 65
Lat 32
Lat 0

3. SEASONS

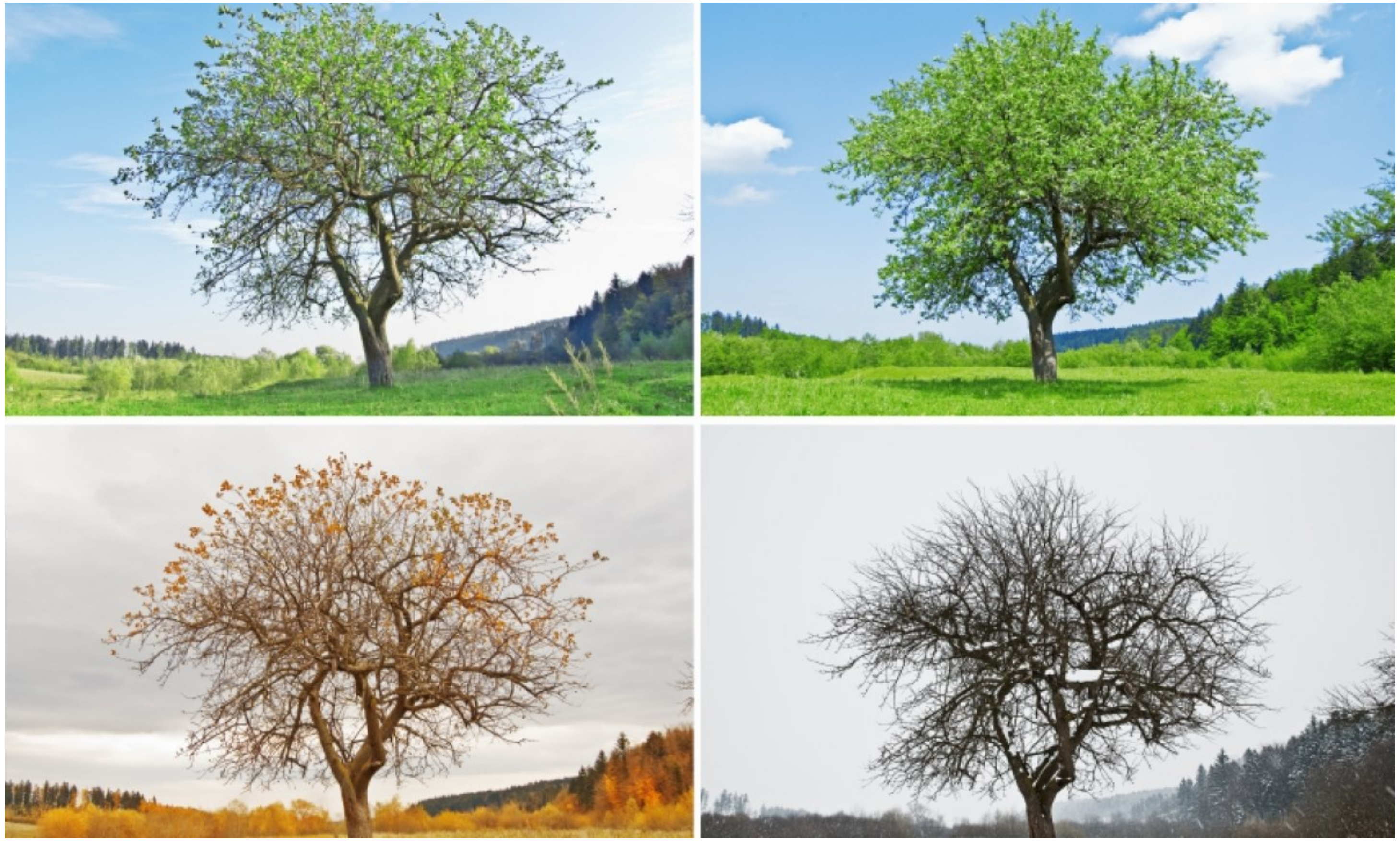
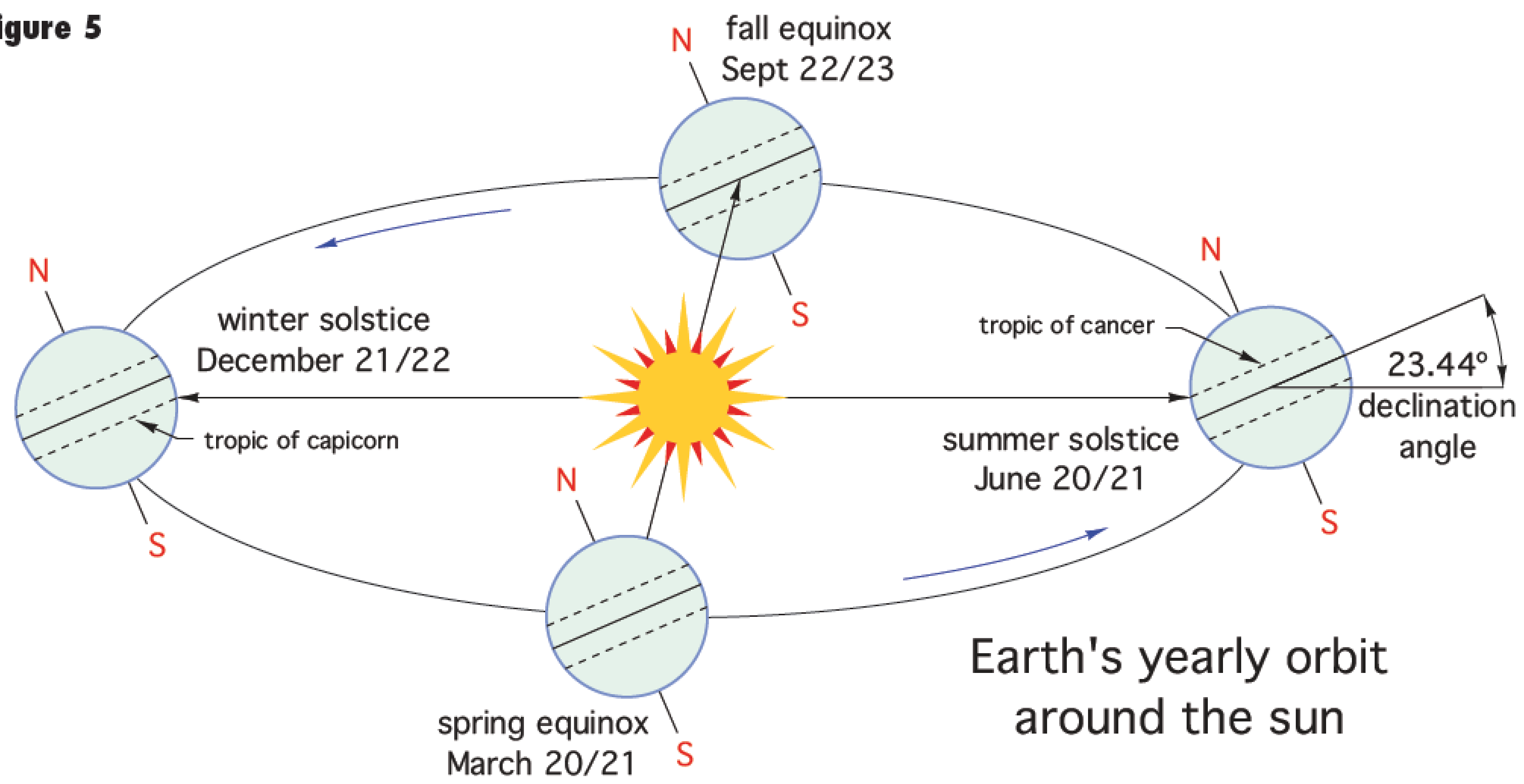
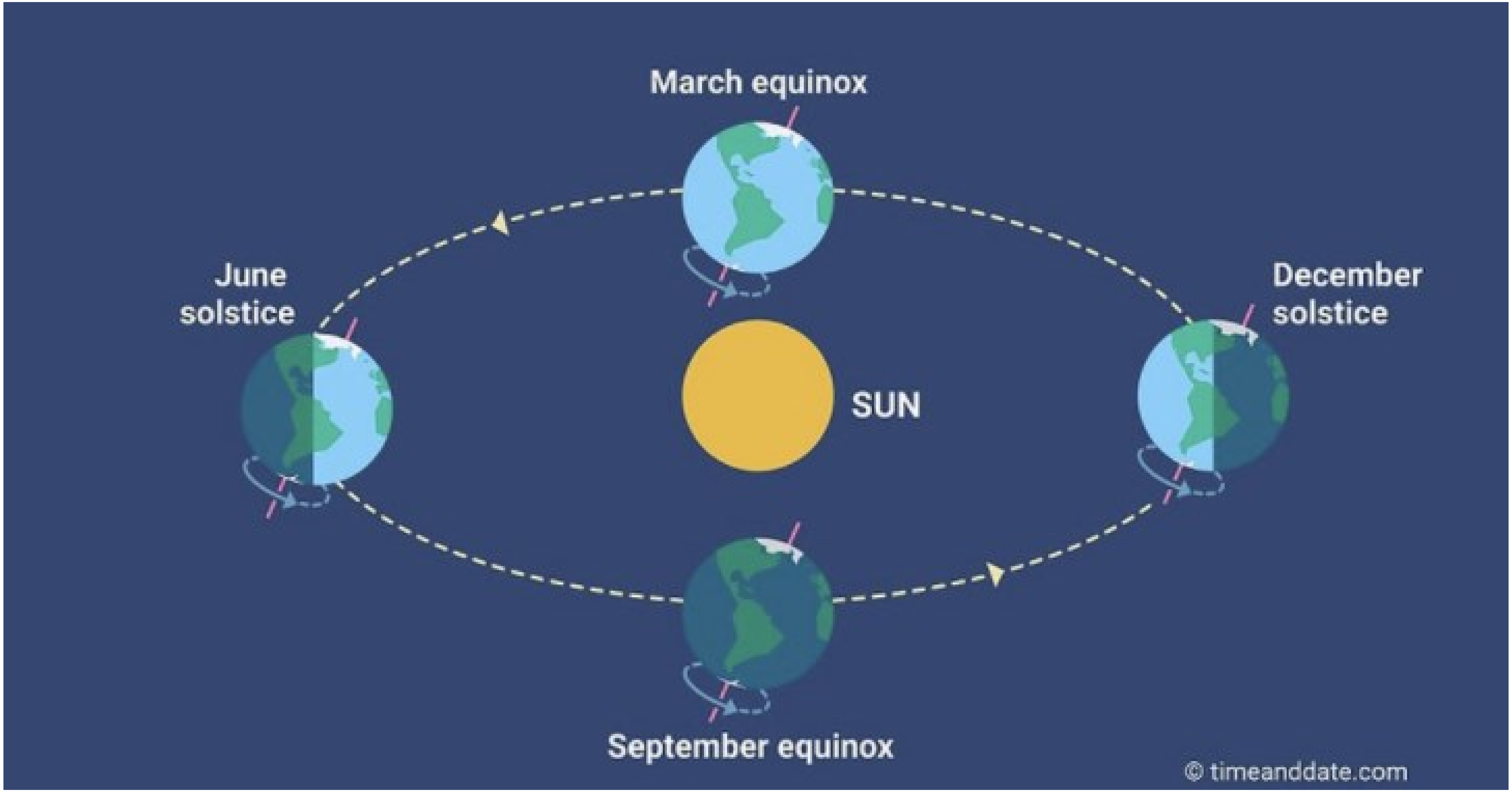
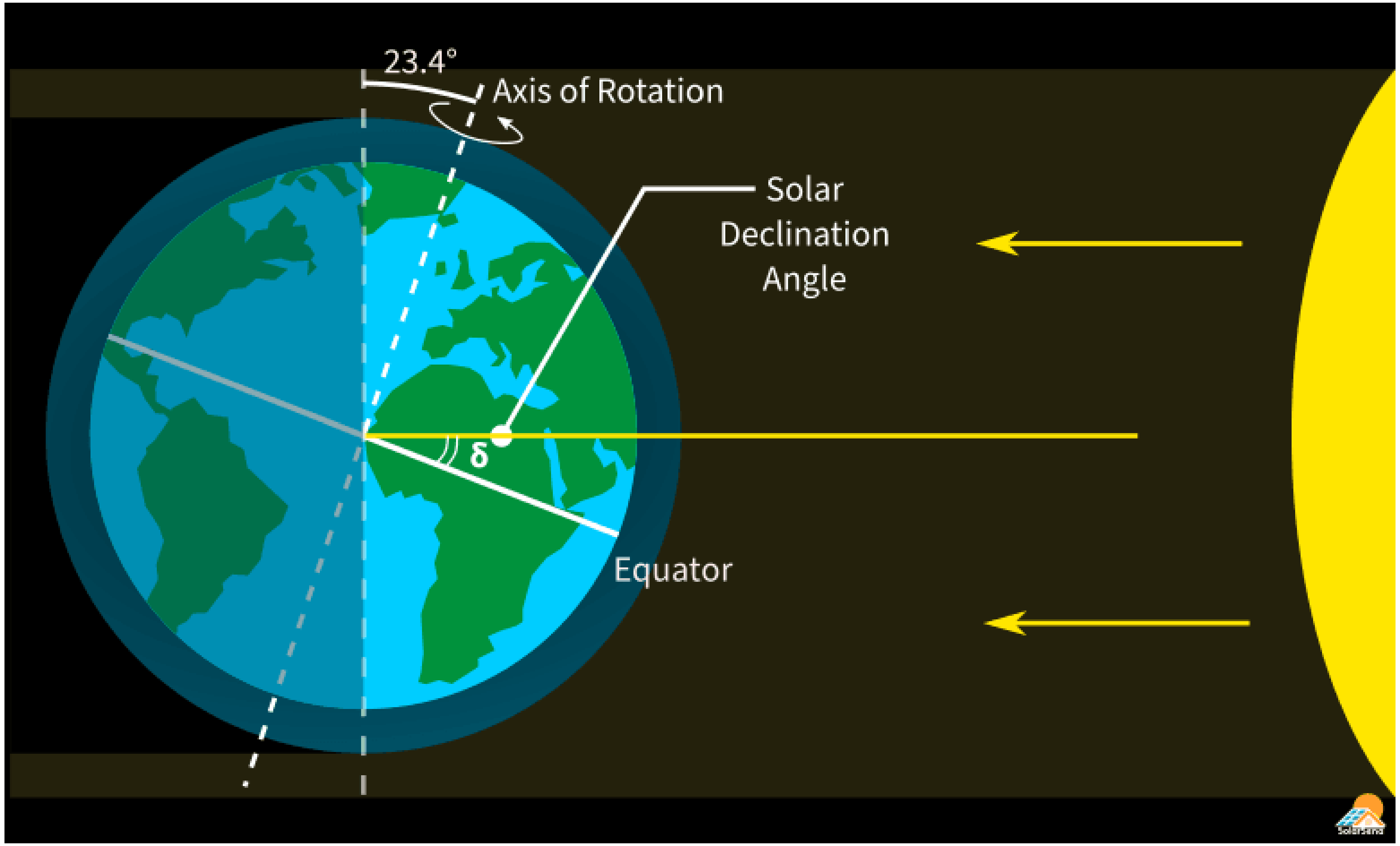


Figure 5

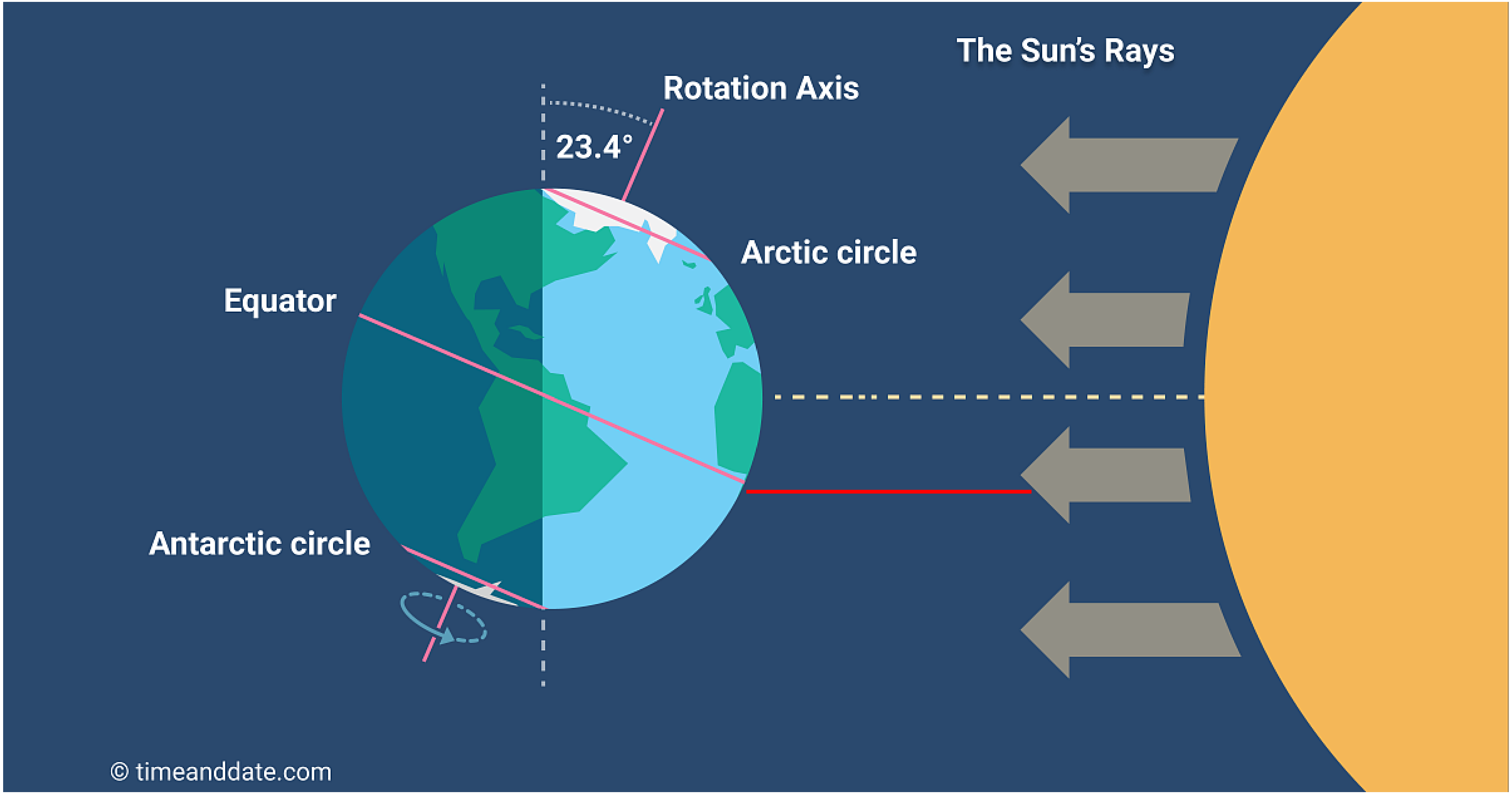

fall equinox
Sept 22/23
N
S
winter solstice
December 21/22
N
S
tropic of capicorn
tropic of cancer
N
S
23.44°
declination
angle
summer solstice
June 20/21
N
S
spring equinox
March 20/21
Earth's yearly orbit
around the sun


March equinox
June
solstice
December
solstice
SUN
September equinox
© timeanddate.com

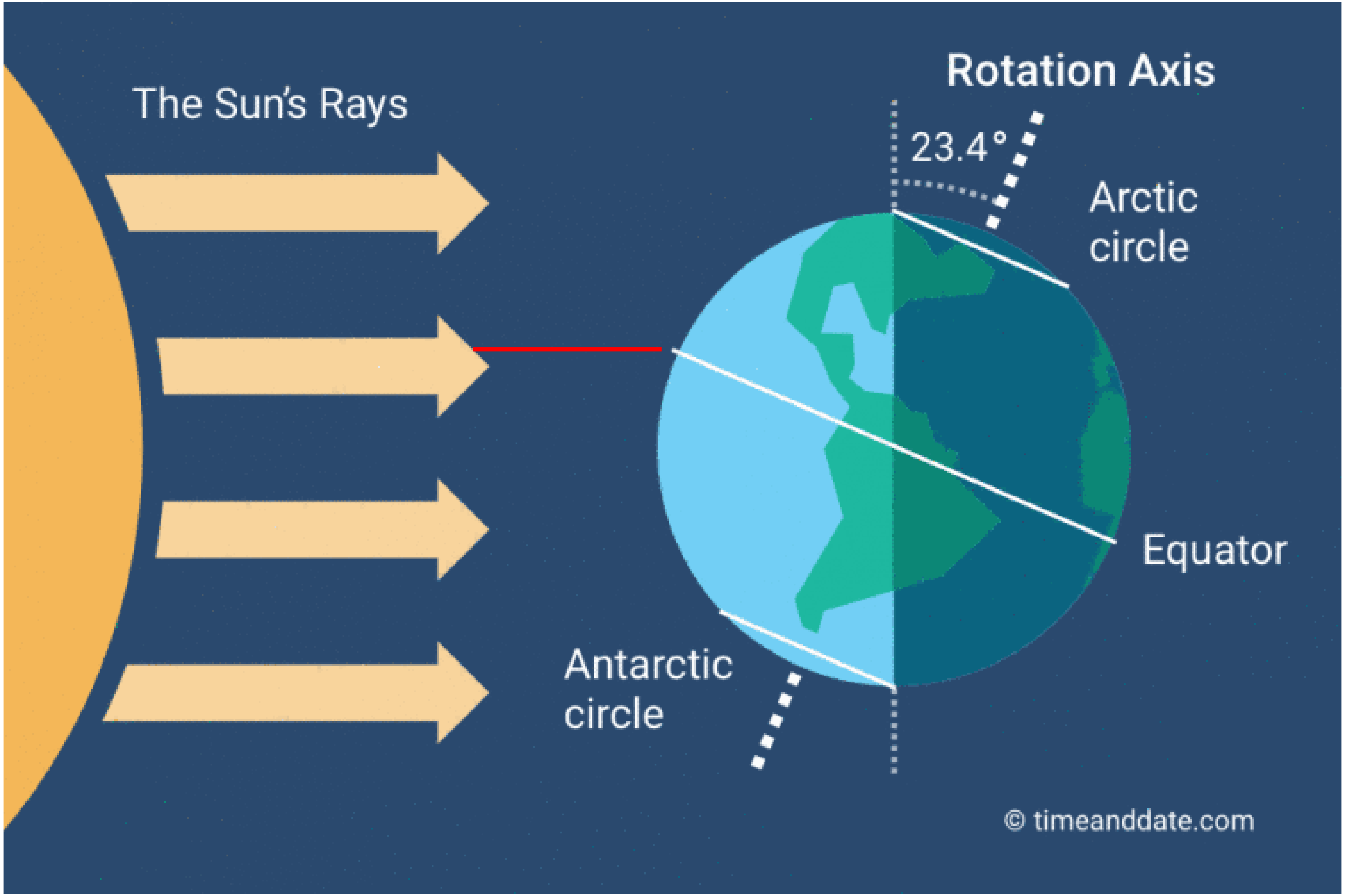

23.4°
Axis of Rotation
Solar
Declination
Angle
δ
Equator

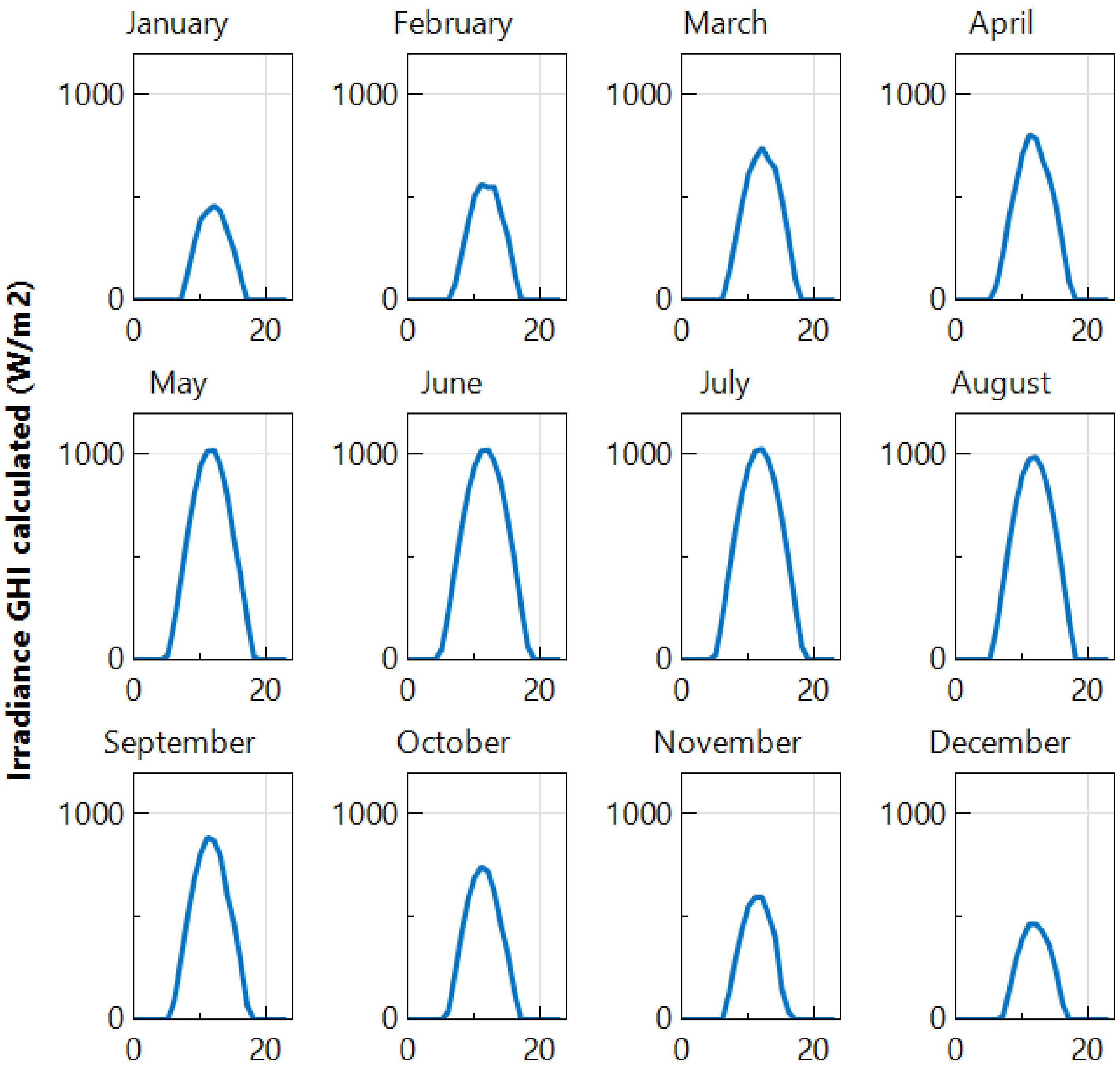

Oblique angles give less
light & heat per unit of area.
www.solarschoolhouse.org


90 degree angles give more
light & heat per unit of area.
www.solarschoolhouse.org

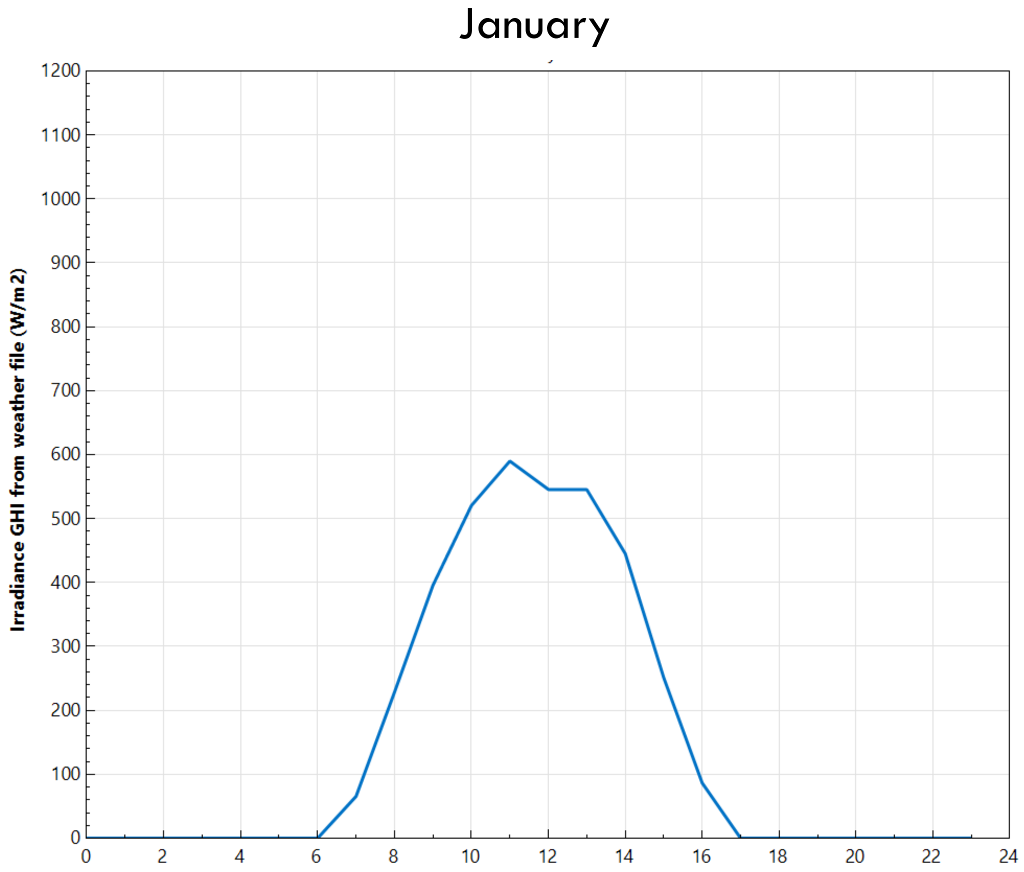


The Sun's Rays
Rotation Axis
23.4°
Arctic circle
Equator
Antarctic circle
© timeanddate.com


The Sun's Rays
Rotation Axis
23.4°
Arctic circle
Equator
Antarctic circle
© timeanddate.com


Irradiance GHI calculated (W/m 2)
January
February
March
April
May
June
July
August
September
October
November
December
1000
0
0
20

TYPICAL DAYS IN JANUARY AND JUNE



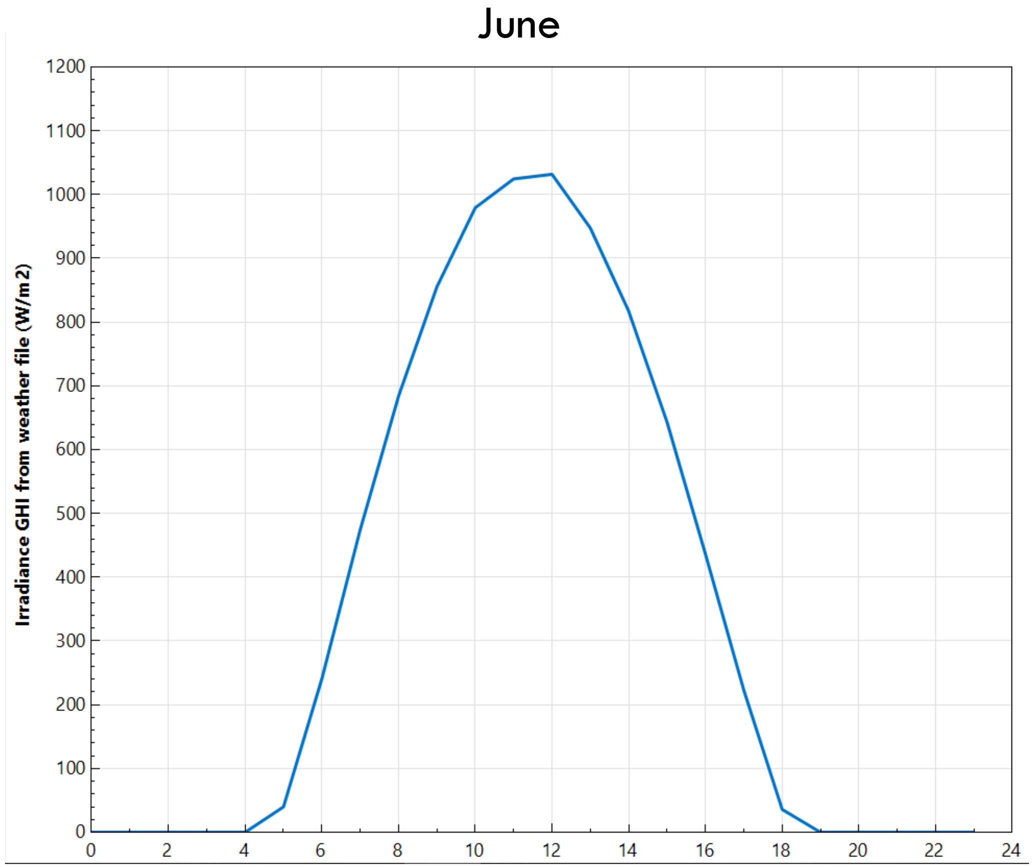
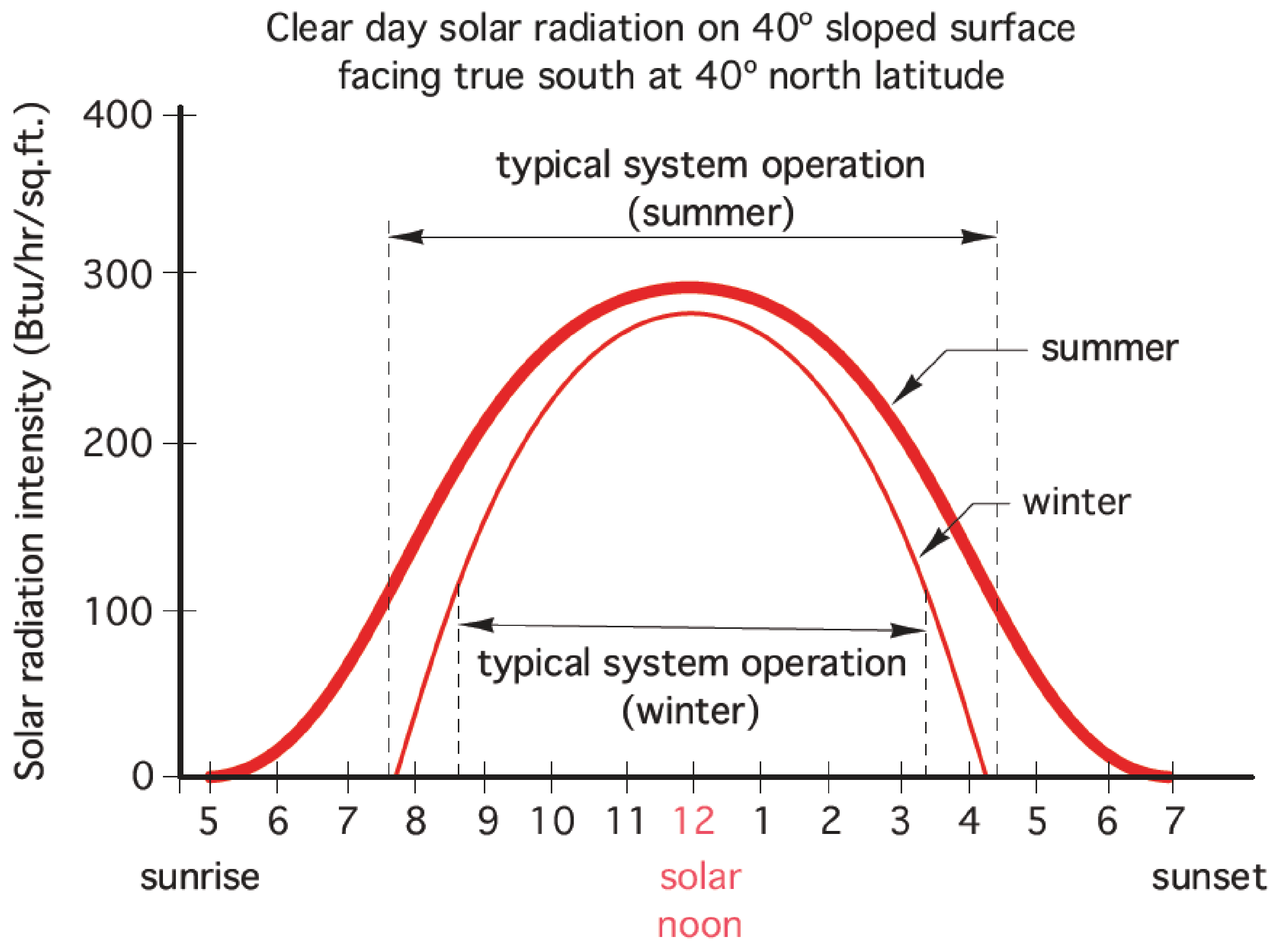
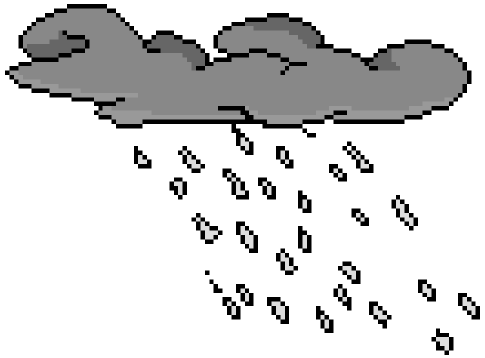


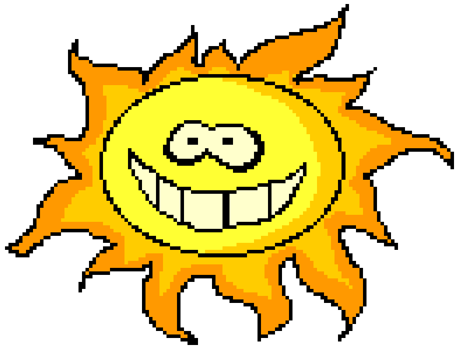
Figure 4


Clear day solar radiation on 40° sloped surface facing true south at 40° north latitude
Solar radiation intensity (Btu/hr/sq.ft.)
400
300
200
100
0
typical system operation (summer)
summer
winter
typical system operation (winter)
5
6
7
8
9
10
11
12
1
2
3
4
5
6
7
sunrise
solar noon
sunset

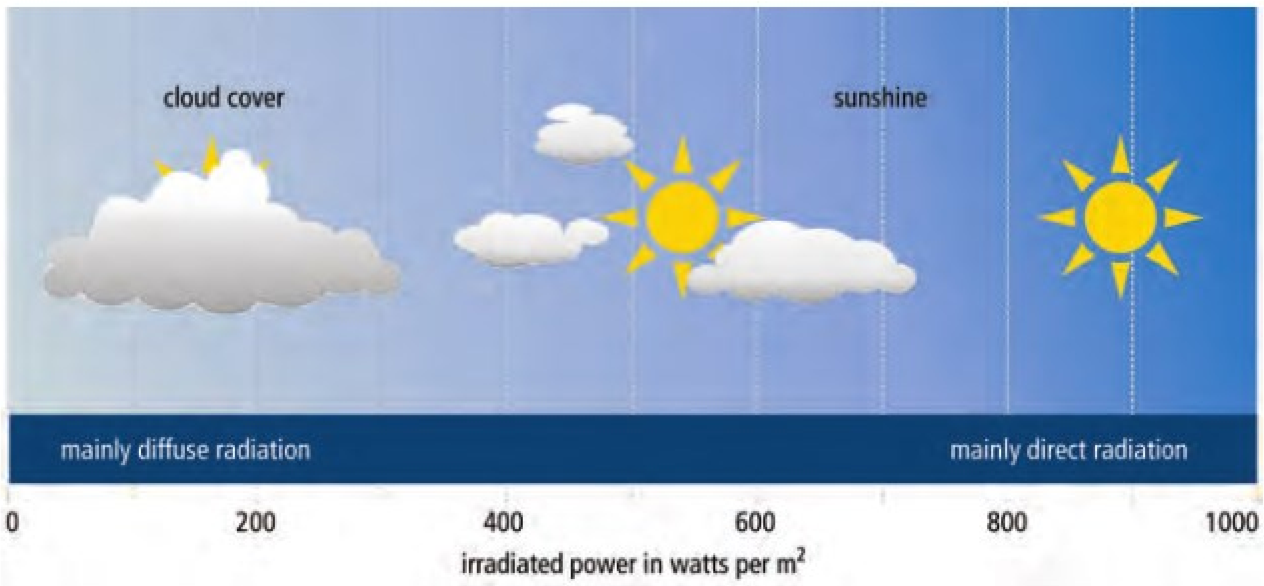
4. WEATHER CONDITIONS

SOLAR RADIATION IS ALEATORY

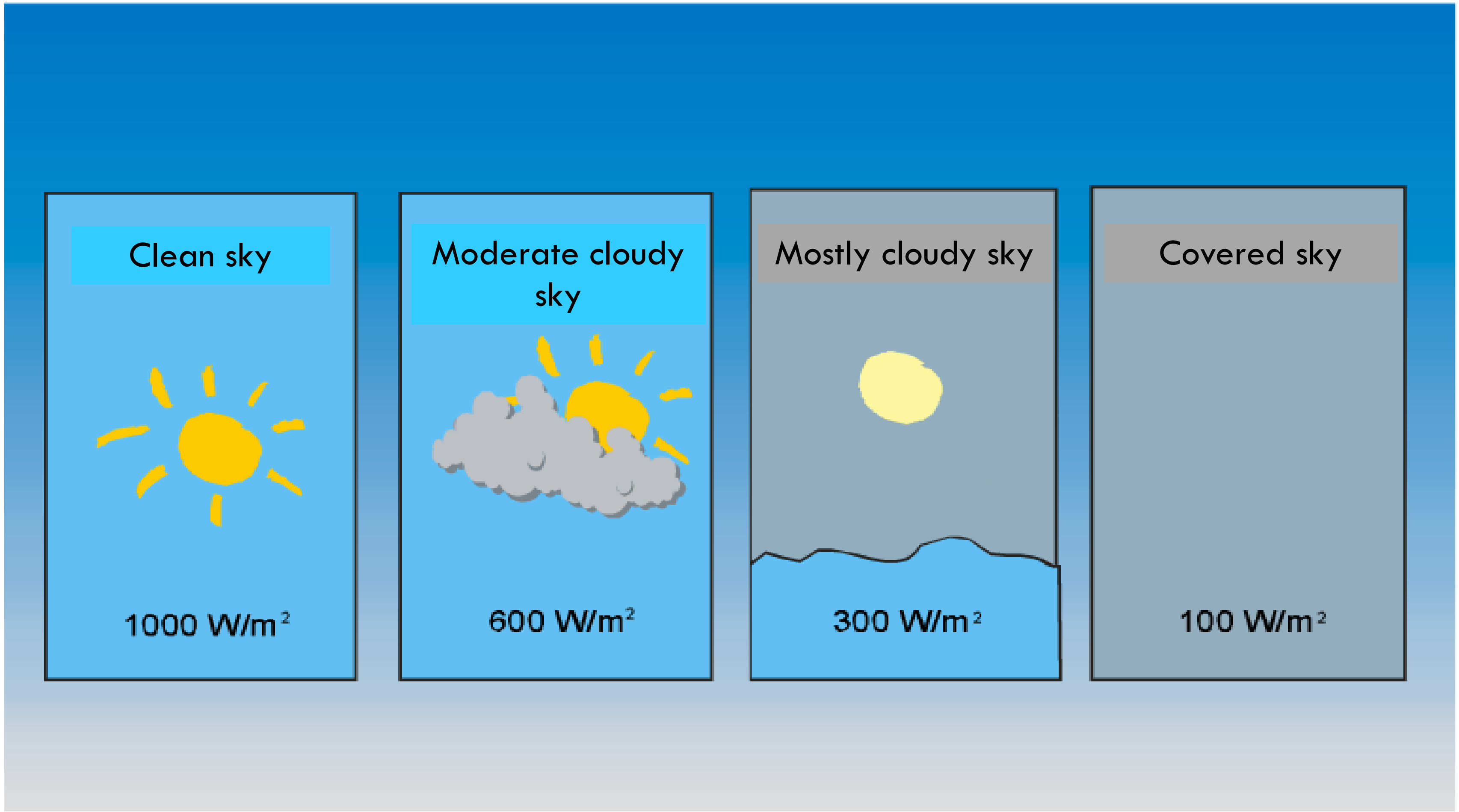




After the general astronomical conditions, the cloud cover or state of the sky is the second decisive factor that has an effect on the supply of solar radiation: both the irradiated power and the proportions of direct and diffuse radiation vary greatly according to the amount of cloud (Figure 1.8).



Solar radiation at ground level



Source: ITW

The sum of direct horizontal irradiance and the diffuse horizontal irradiance (DHI) results in the total irradiance or global horizontal irradiance:

$$G = G_d + G_b = \mathrm{DHI} + \mathrm{DNI}/\cos(\theta_z)$$

WHERE CAN RADIATION DATA BE FOUND?

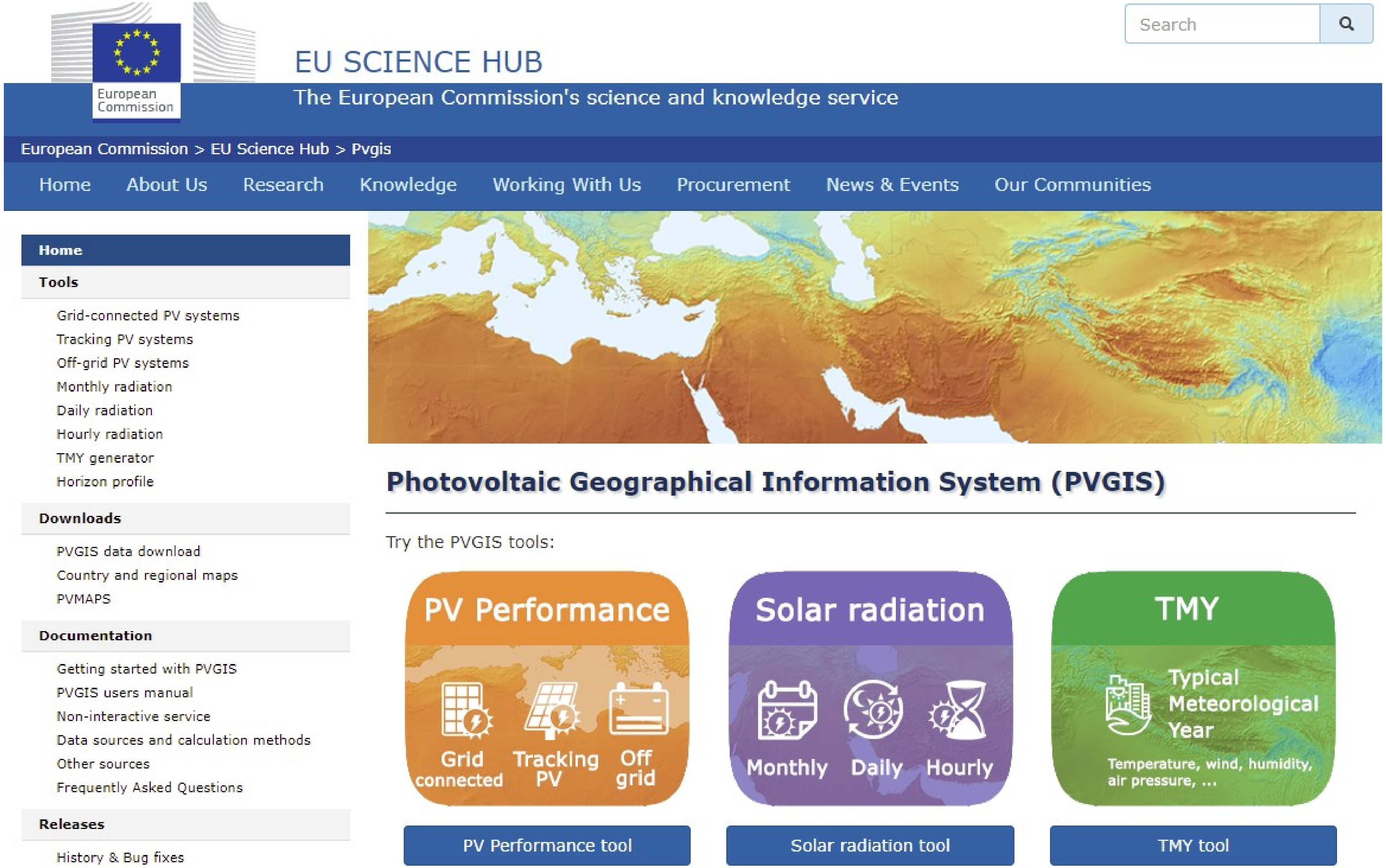
Meteonorm:
http://www.meteonorm.com/media/maps_online/gh_map_africa.pdf

PV GIS:
http://re.jrc.ec.europa.eu/pvgis/countries/afr/4-gs13.png

NASA:
http://swera.unep.net/index.php?id=wms_compliant

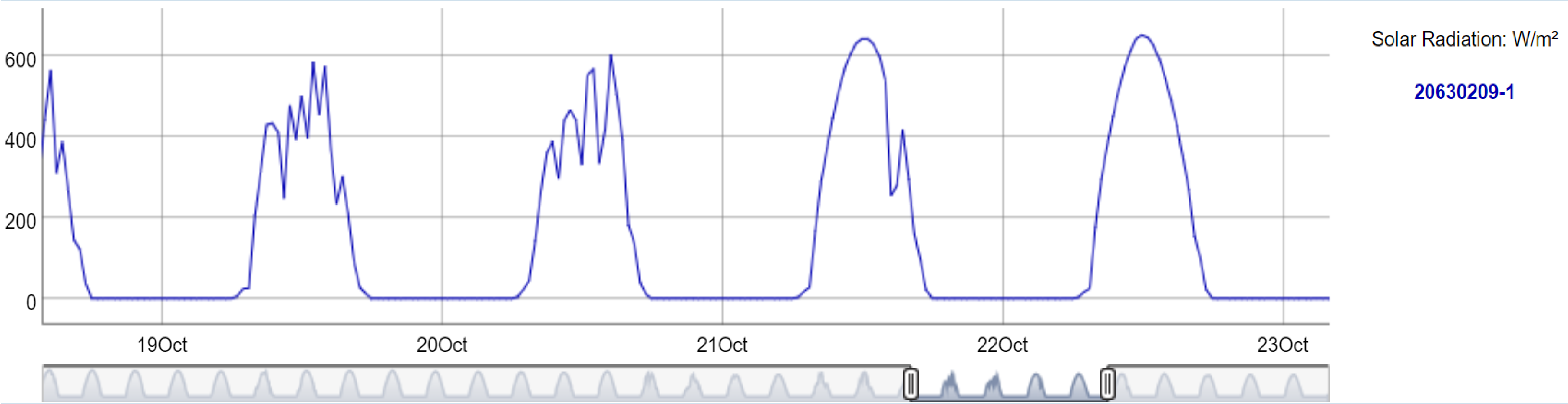
Design Software: T*Sol, Transol, Polysun

NREA solar atlas

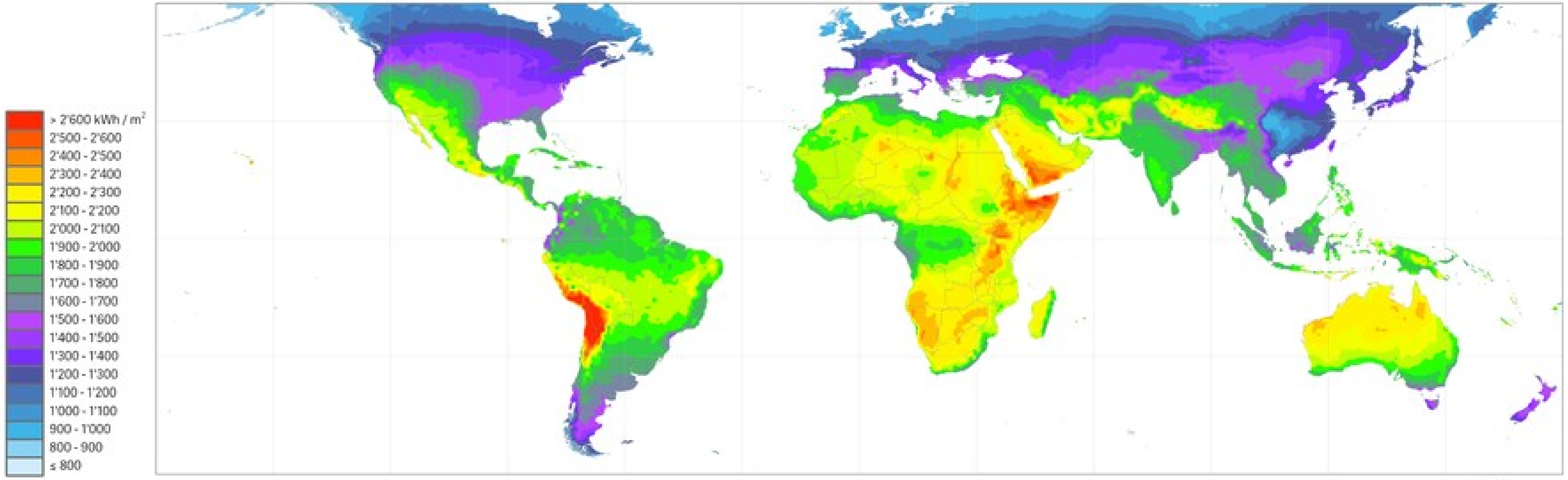


https://re.jrc.ec.europa.eu/pvg_tools/en/#MR

OCTOBER 2021- AMMAN



Yearly sum of Global Horizontal Irradiation (GHI)



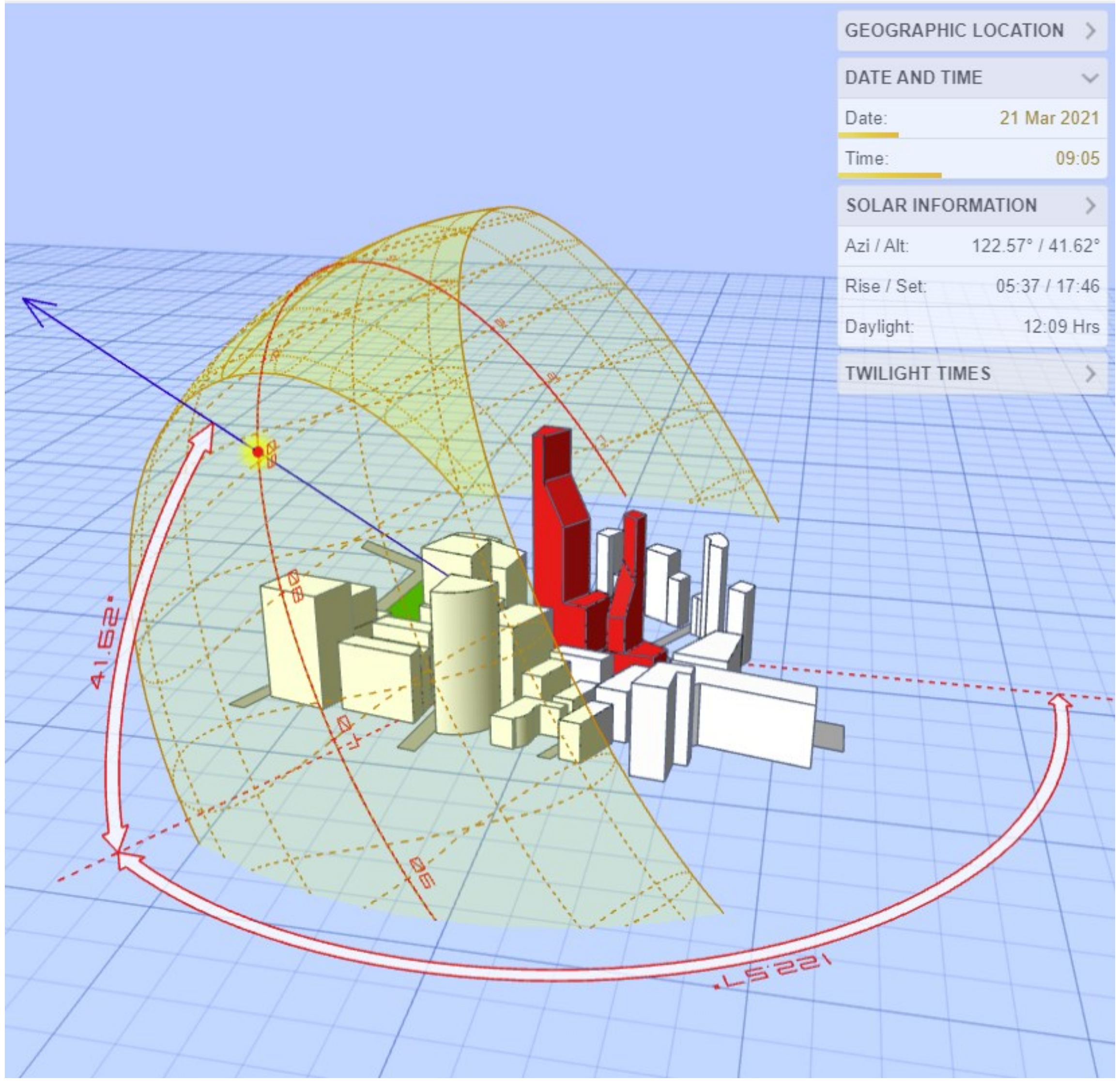
Source: Meteonorm 8 (www.meteonorm.com); uncertainty 6%
Period: 1996-2015; grid cell size: 0.0625°

meteonorm Meteotest

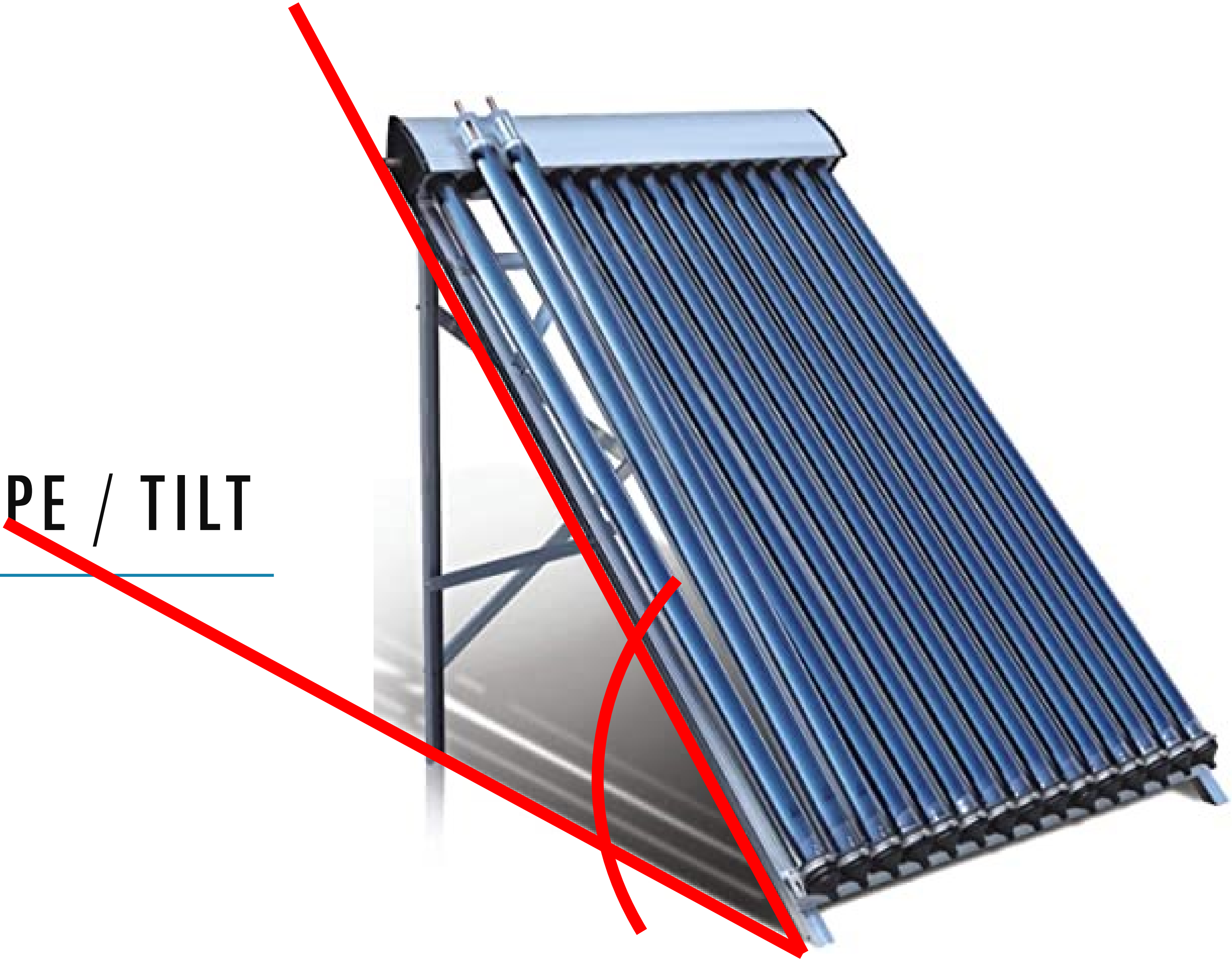
ORIENTATION

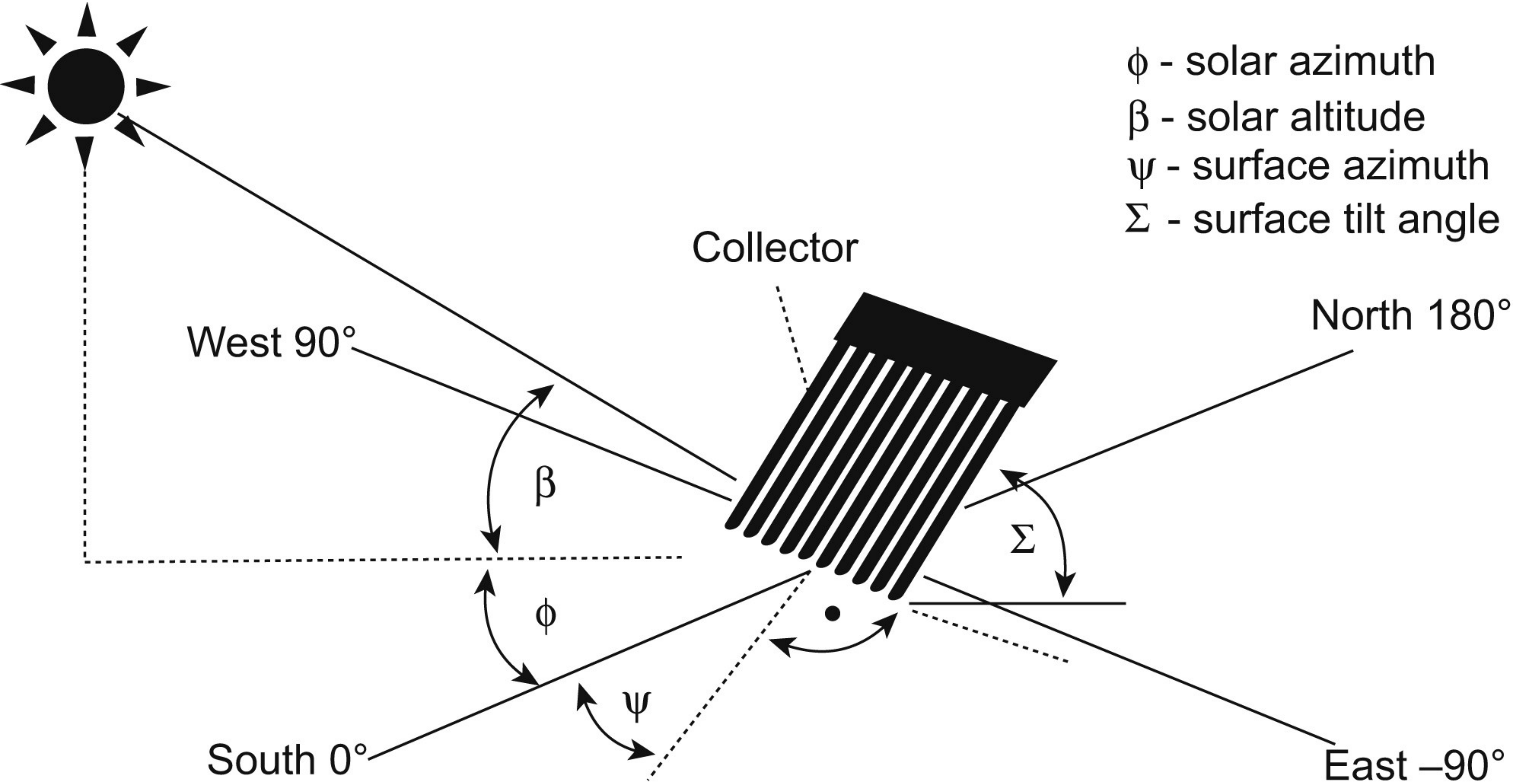
SUN LOCATION

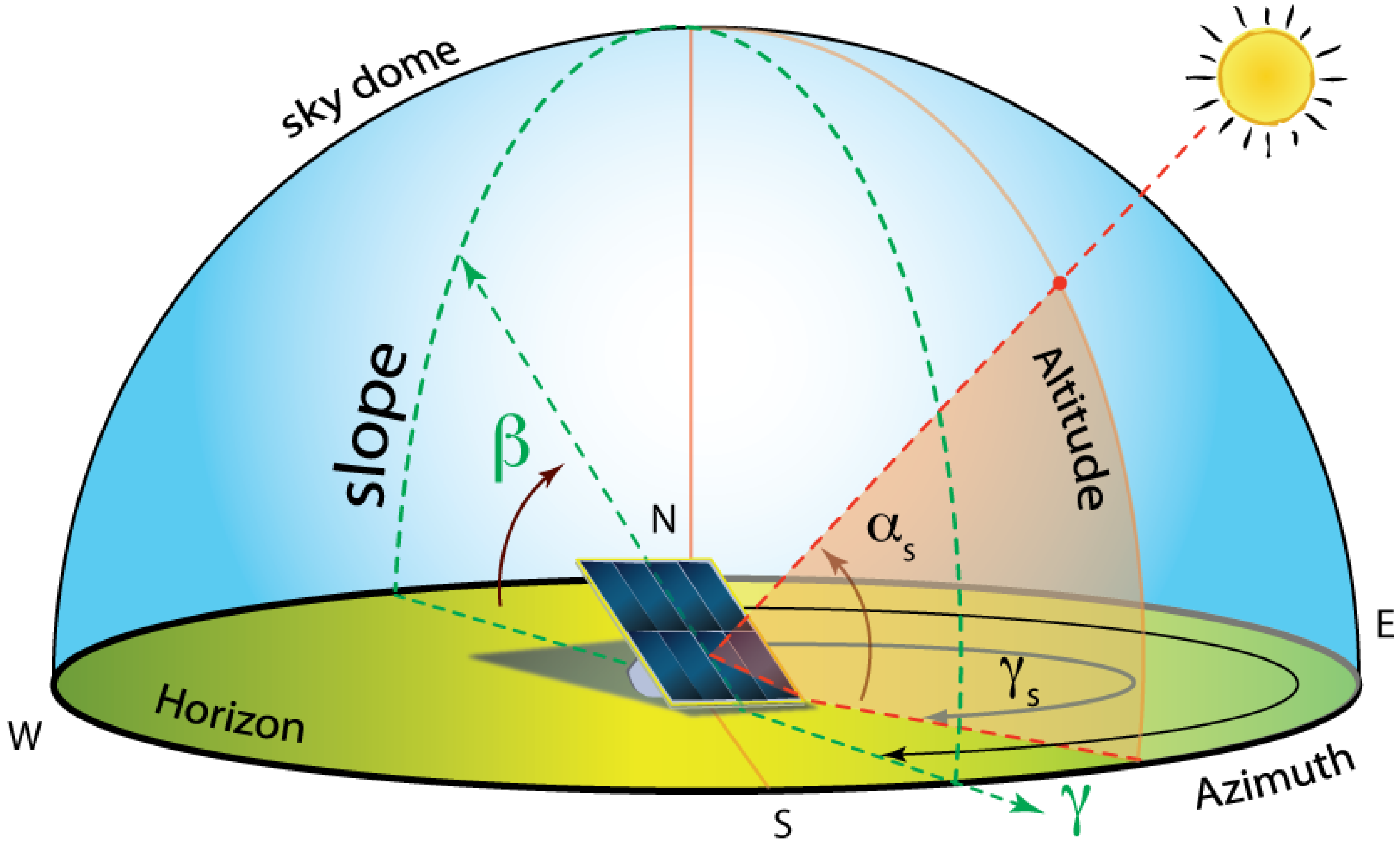
SOLAR ALTITUDE
SOLAR AZIMUTH



COLLECTOR SLOPE / TILT




ϕ - solar azimuth
β - solar altitude
ψ - surface azimuth
Σ - surface tilt angle
Collector
North 180°
West 90°
β
Σ
ϕ
ψ
South 0°
East –90°

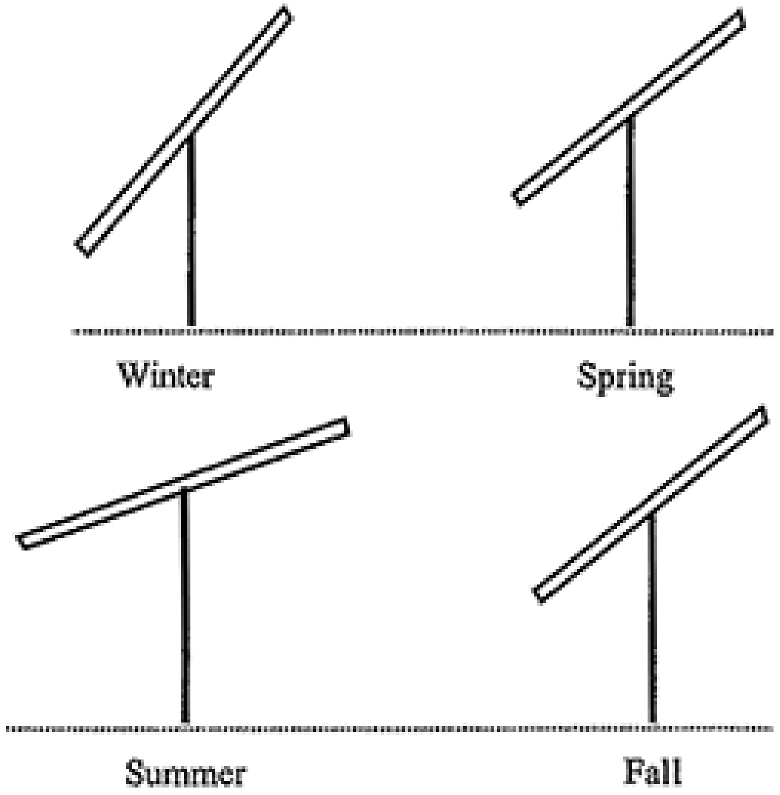

sky dome
slope
β
N
Altitude
α_s
E
γ_s
W
Horizon
S
γ
Azimuth

SLOPE (TILT), B

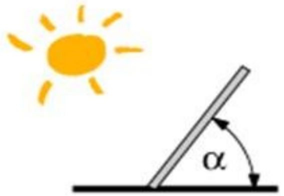
The angle between the plane of the surface in question and the horizontal:

$0° \leq \boldsymbol{\beta} \leq 180°$

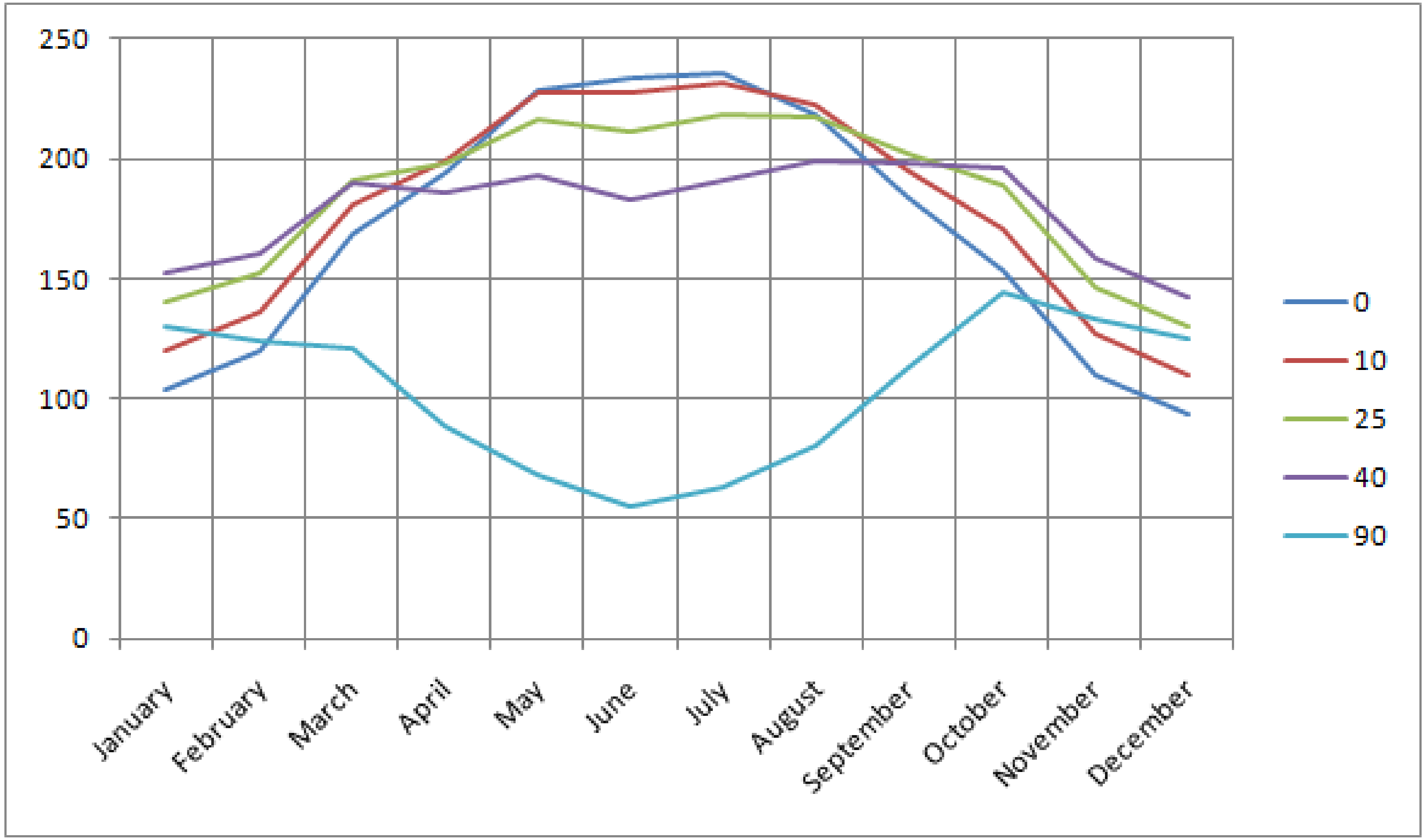
$\boldsymbol{\beta} \geq 90°$ means that the surface has a downward-facing component.



Radiation on sloped surfaces

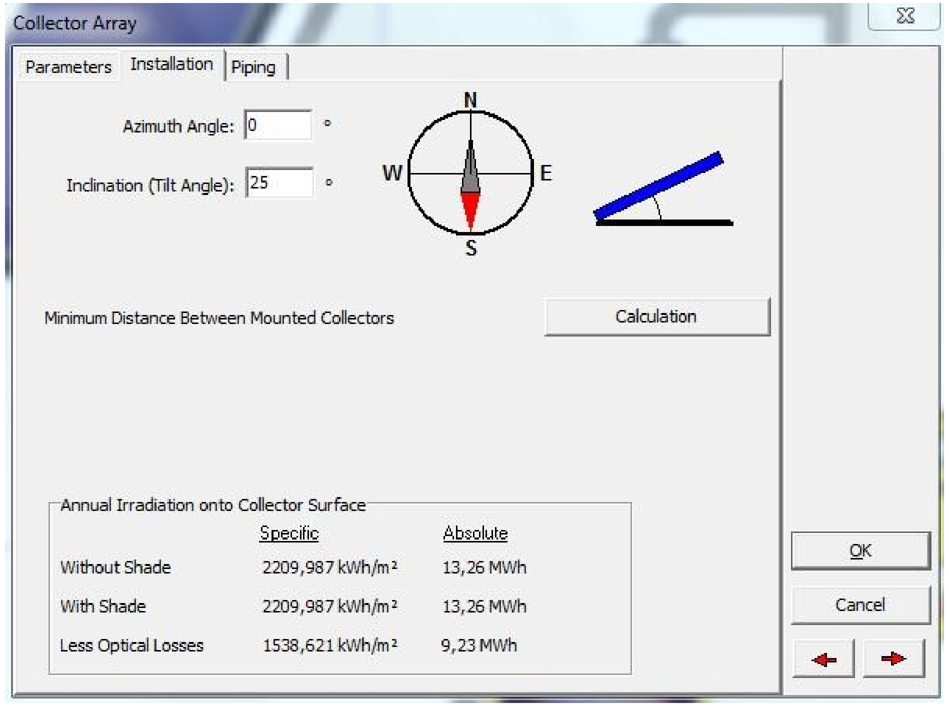


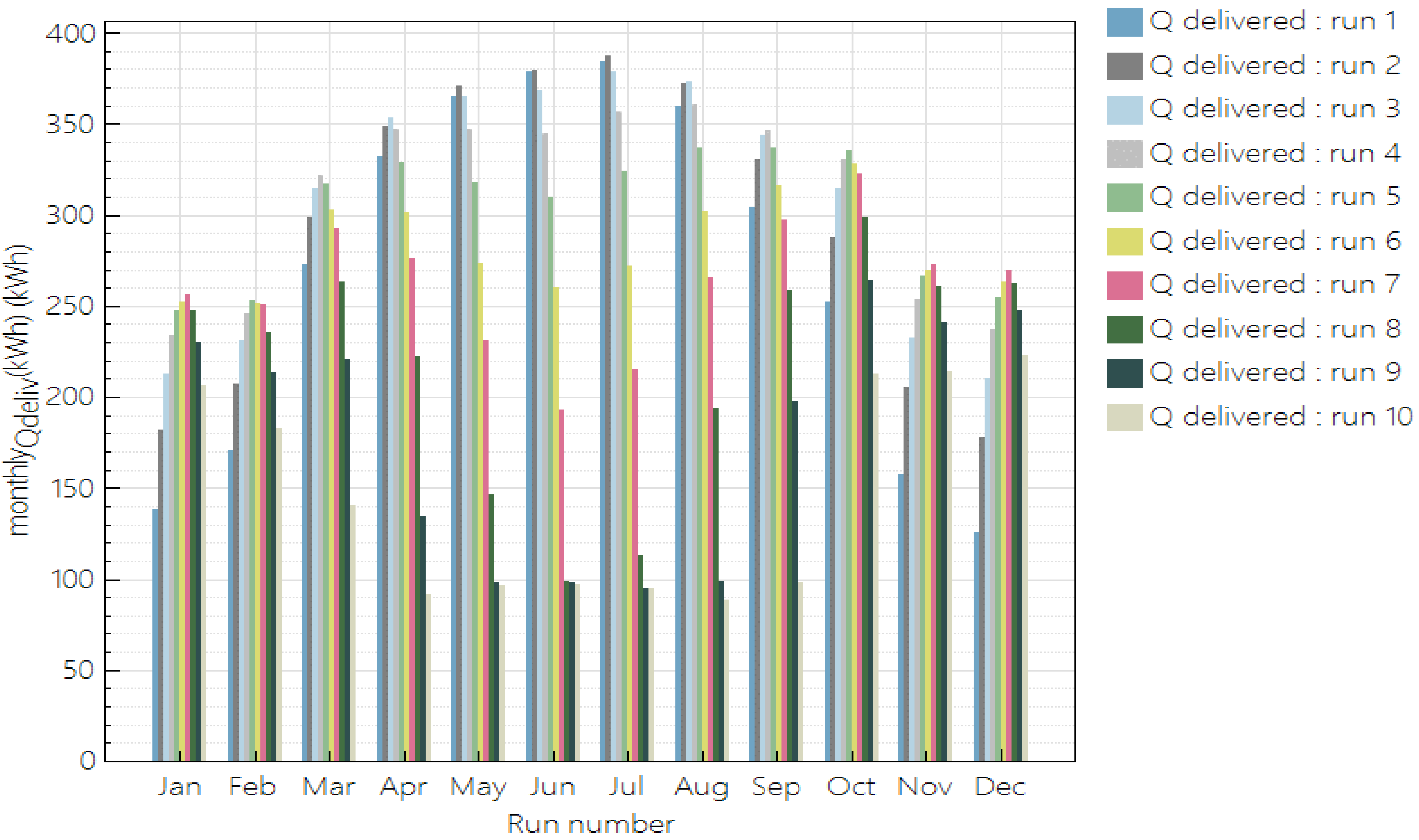
[kWh/(m² month)]



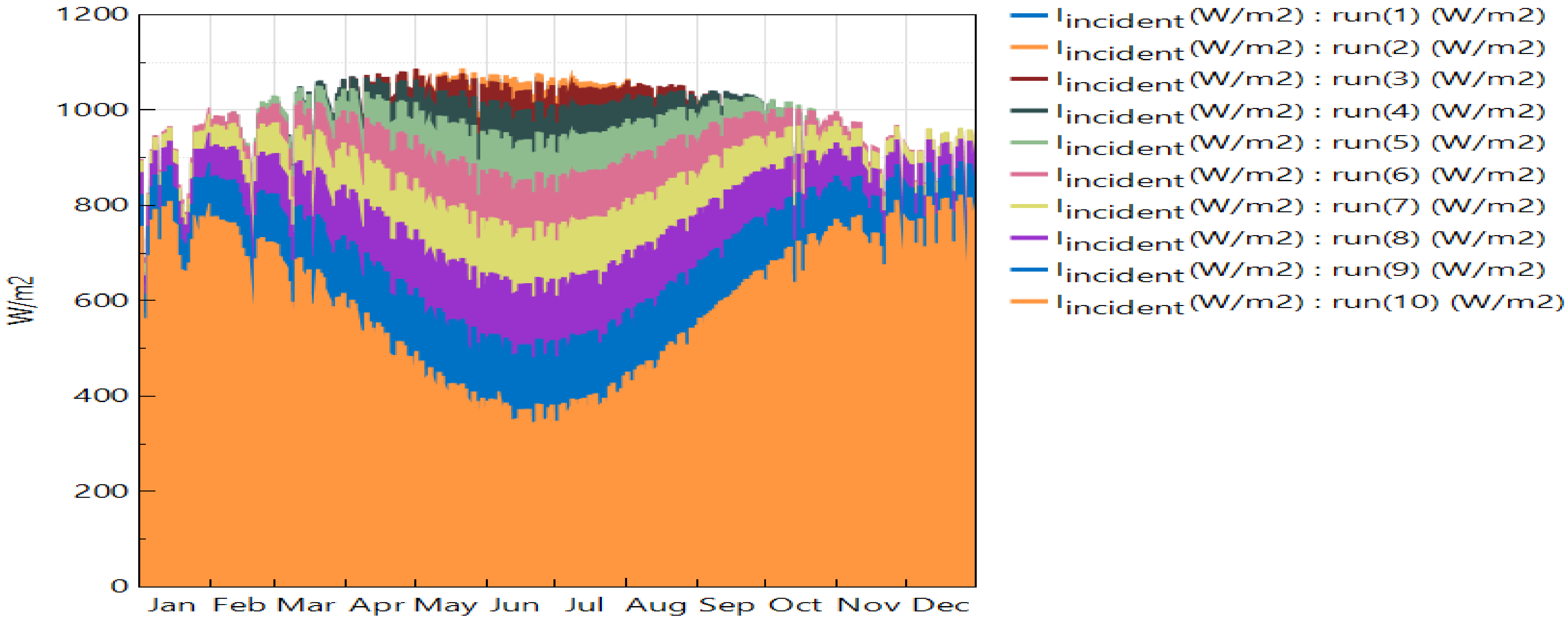
Optimal slope angle

slope [°]	kWh / (m2 a)
0	2040
10	2145
20	2200
25	2210
30	2200
40	2150
50	2050
60	1900
70	1715
80	1490
90	1250





Q delivered : run 1
Q delivered : run 2
Q delivered : run 3
Q delivered : run 4
Q delivered : run 5
Q delivered : run 6
Q delivered : run 7
Q delivered : run 8
Q delivered : run 9
Q delivered : run 10
monthlyQdeliv(kWh) (kWh)
Run number
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
0
50
100
150
200
250
300
350
400



1200
1000
800
600
400
200
0
W/m2
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
I incident (W/m2) : run(1) (W/m2)
I incident (W/m2) : run(2) (W/m2)
I incident (W/m2) : run(3) (W/m2)
I incident (W/m2) : run(4) (W/m2)
I incident (W/m2) : run(5) (W/m2)
I incident (W/m2) : run(6) (W/m2)
I incident (W/m2) : run(7) (W/m2)
I incident (W/m2) : run(8) (W/m2)
I incident (W/m2) : run(9) (W/m2)
I incident (W/m2) : run(10) (W/m2)

Losses due to different slope and orientation

	West					East
	90	60	30	0	-30	-60	-90
0	92	92	92	92	92	92	92
10	91	94	96	97	96	94	91
20	89	94	98	99,6	98	94	89
25	87	94	98	100	98	94	87
30	85	93	98	99,7	98	93	85
90	51	57	58	56	58	57	51

Example of monthly values

	G Horizontal
	[kWh/m²]
January	103
February	120
March	168
April	194
May	228
June	233
July	235
August	219
September	184
October	153
November	109
December	94
Year	**2040**

Source: T Sol

The 100 MW "Shams 1" Parabolic Trough plant is the largest solar plant under development in the region, and will likely be the largest in the world once completed in 2012 (although the 392 MW Ivanpah will likely eclipse it shortly thereafter). The recently released GTM Research report CSP 2011 contains detailed project specs for every one of the 195 CSP projects in operation or under development globally.

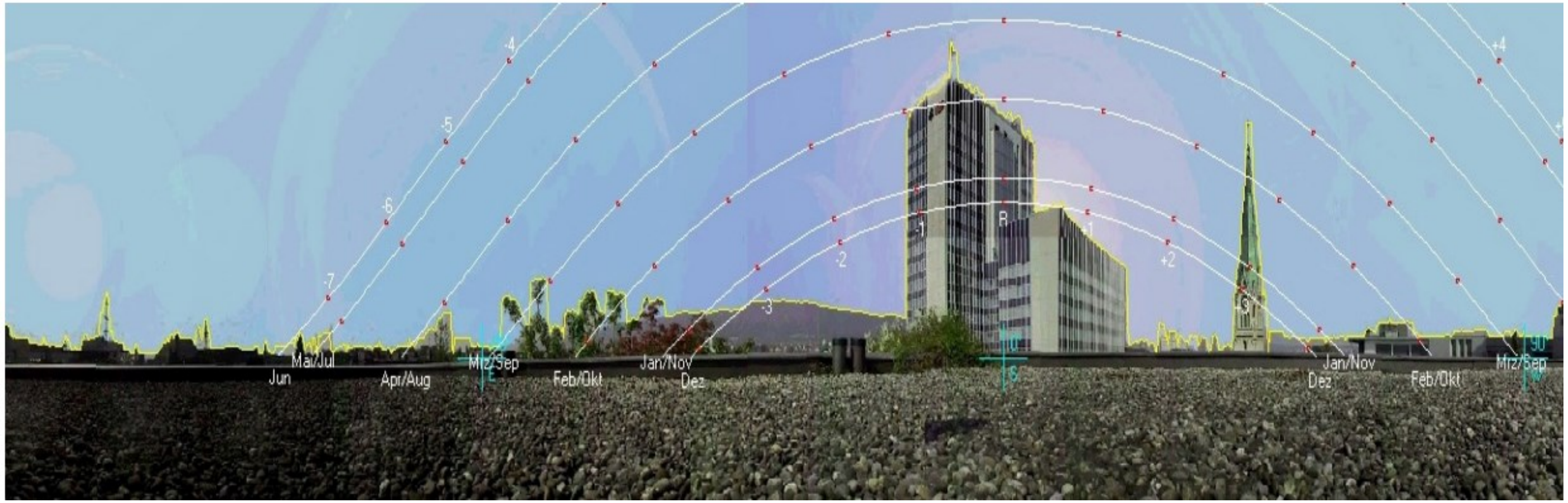
While there were some hiccups in the early days of the project, since the triple handshake of Abengoa/Total/Masdar in July 2010, things seem to be back on track and progressing smoothly. A quick re-cap of the timeline:

May 2009: Project put on hold, when DNI estimate was reduced by 12.5%
July 2010: Construction started
July 2012: Expected commissioning

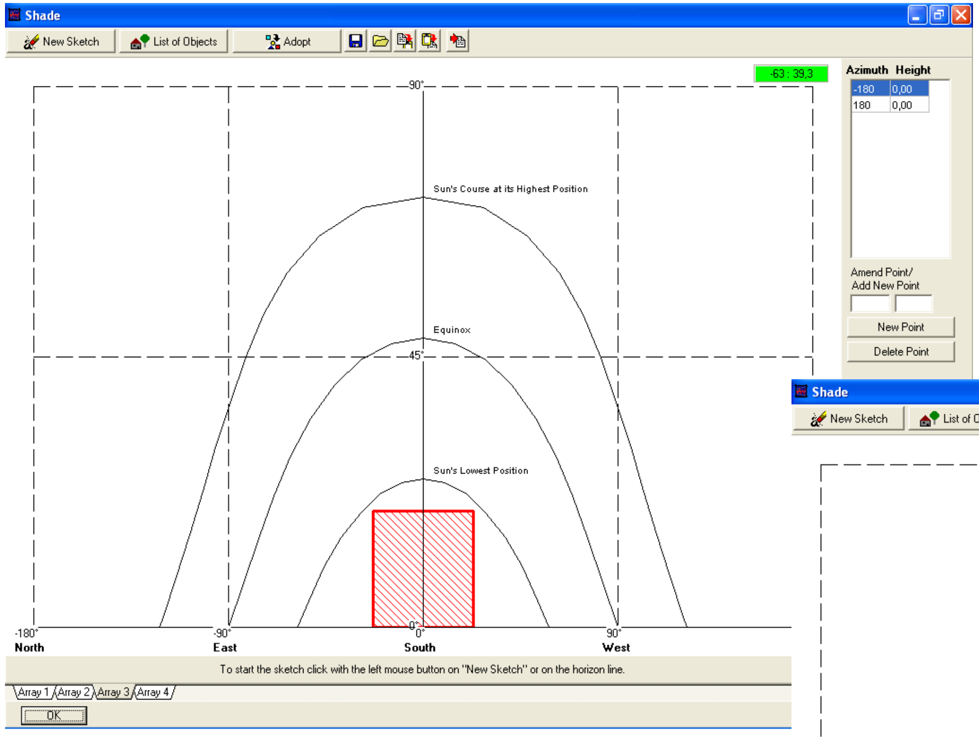
SHAMS – 1

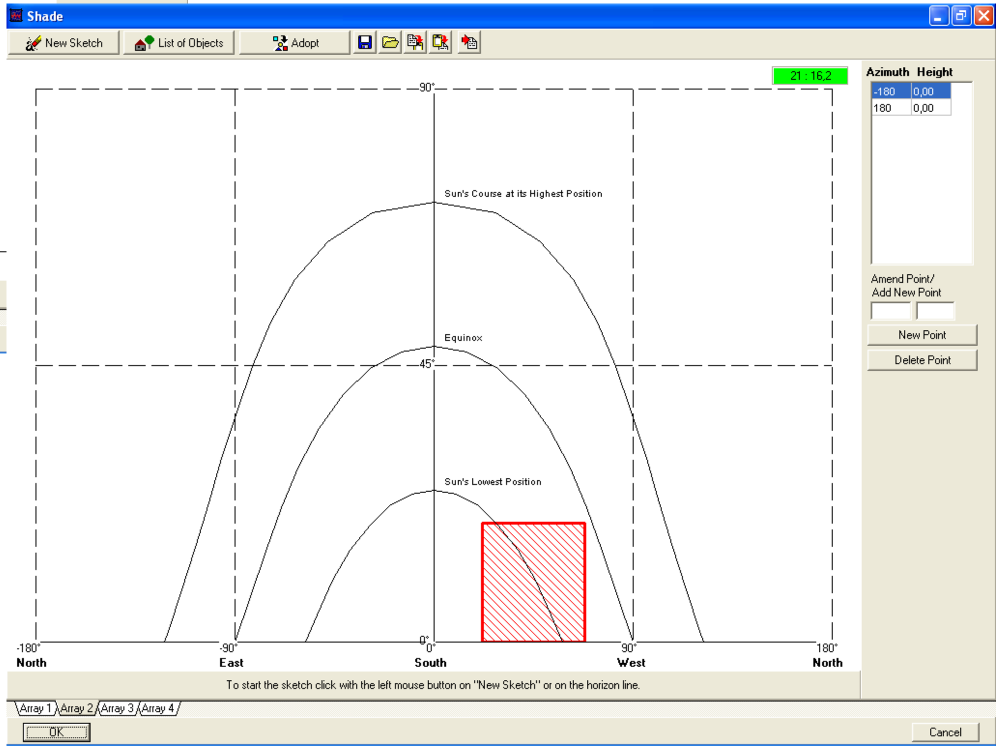
Shadows

- thumb estimation
- evaluation of obstacles’ coordinates
- compass and clinometer
- sofwares (evaluation of basic obstacles’ geometric data)


-4
-5
-6
-7
-3
-2
-1
R
1
+2
3
+4
Jun
Mai/Jul
Apr/Aug
Mrz/Sep
Feb/Okt
Jan/Nov
Dez
Dez
Jan/Nov
Feb/Okt
Mrz/Sep

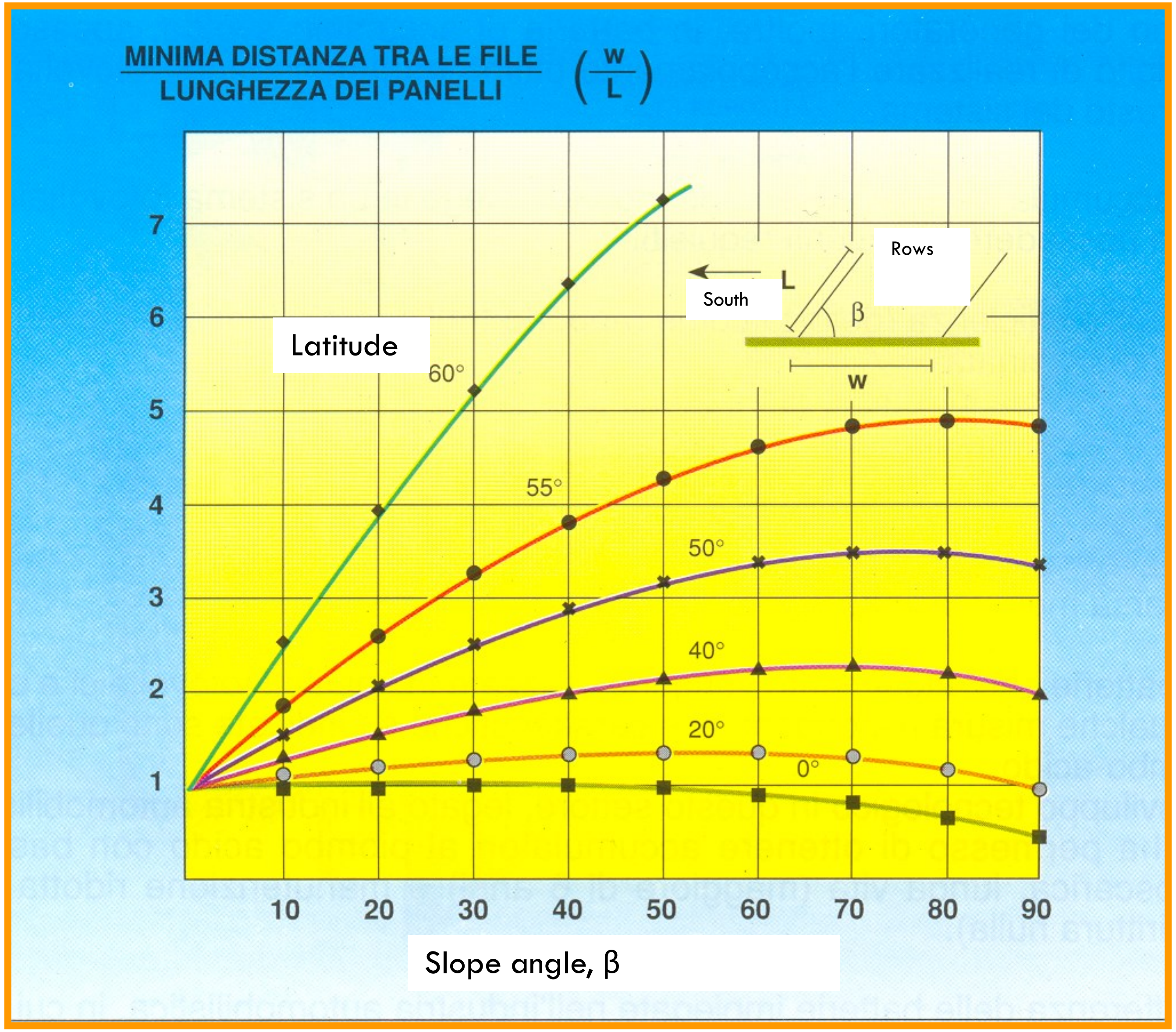
Same obstacle in different positions



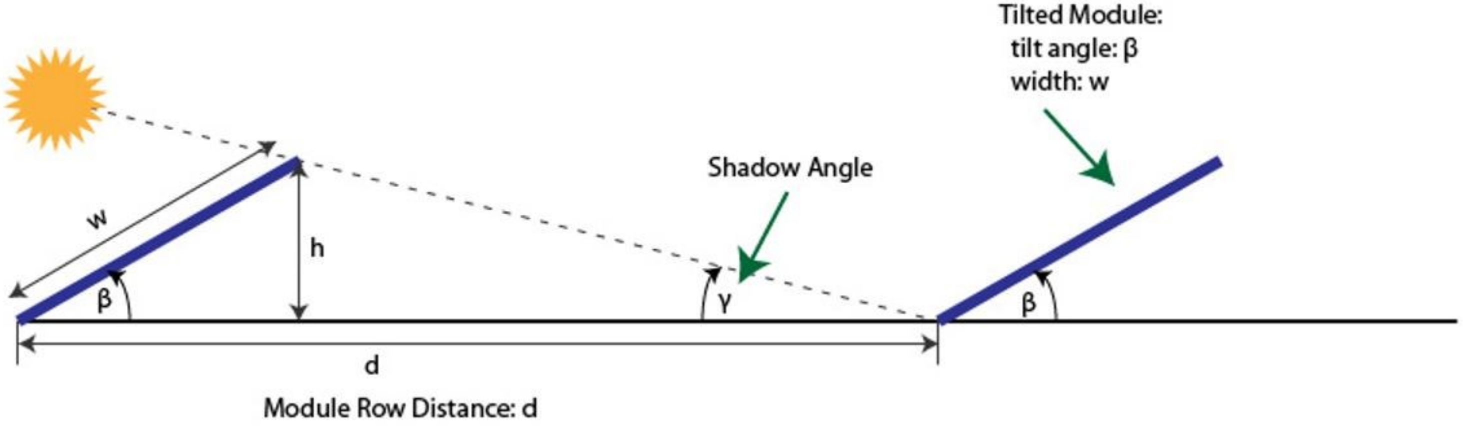


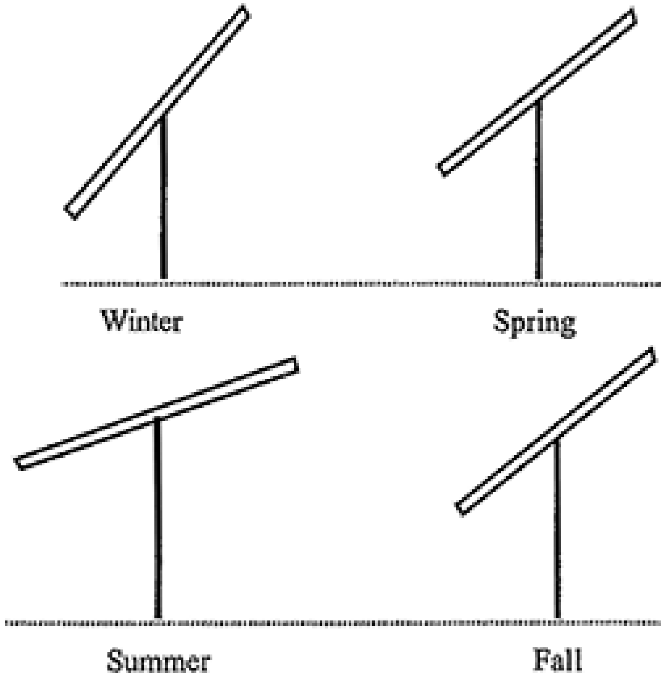
Shadow effect between collector rows

$$\frac{\text{Min. distance between rows}}{\text{Collector's lenght}} = \frac{W}{L}$$



Source: ENEA


Tilted Module:
tilt angle: β
width: w
w
h
β
Shadow Angle
γ
β
d
Module Row Distance: d


Winter
Spring
Summer
Fall

SOLAR RADIATION MEASUREMENT

MEASUREMENT INSTRUMENTS

Name	Type of Receiver	Use	Comment
Pyranometer	Thermopile	Outdoor global measurements	Very high accuracy, slow response
Photovoltaic Sensor (Solarimeter)	Solar Cell	Outdoor global measurements	High accuracy, fast response
Reference Cell	Solar Cell	Indoor calibration	
Spectroradiometer	Photodiode or CCD	Spectral measurements	Slow, medium accuracy
Campbell Stokes	Cardboard strips	Sunshine hours	Crude
Satellite Photo	Film/CCD	Estimation of global irradiation, cloud cover	Broad coverage

CAMBELL-STOKES SUNSHINE RECORDER

THERMOPILE PYRANOMETER

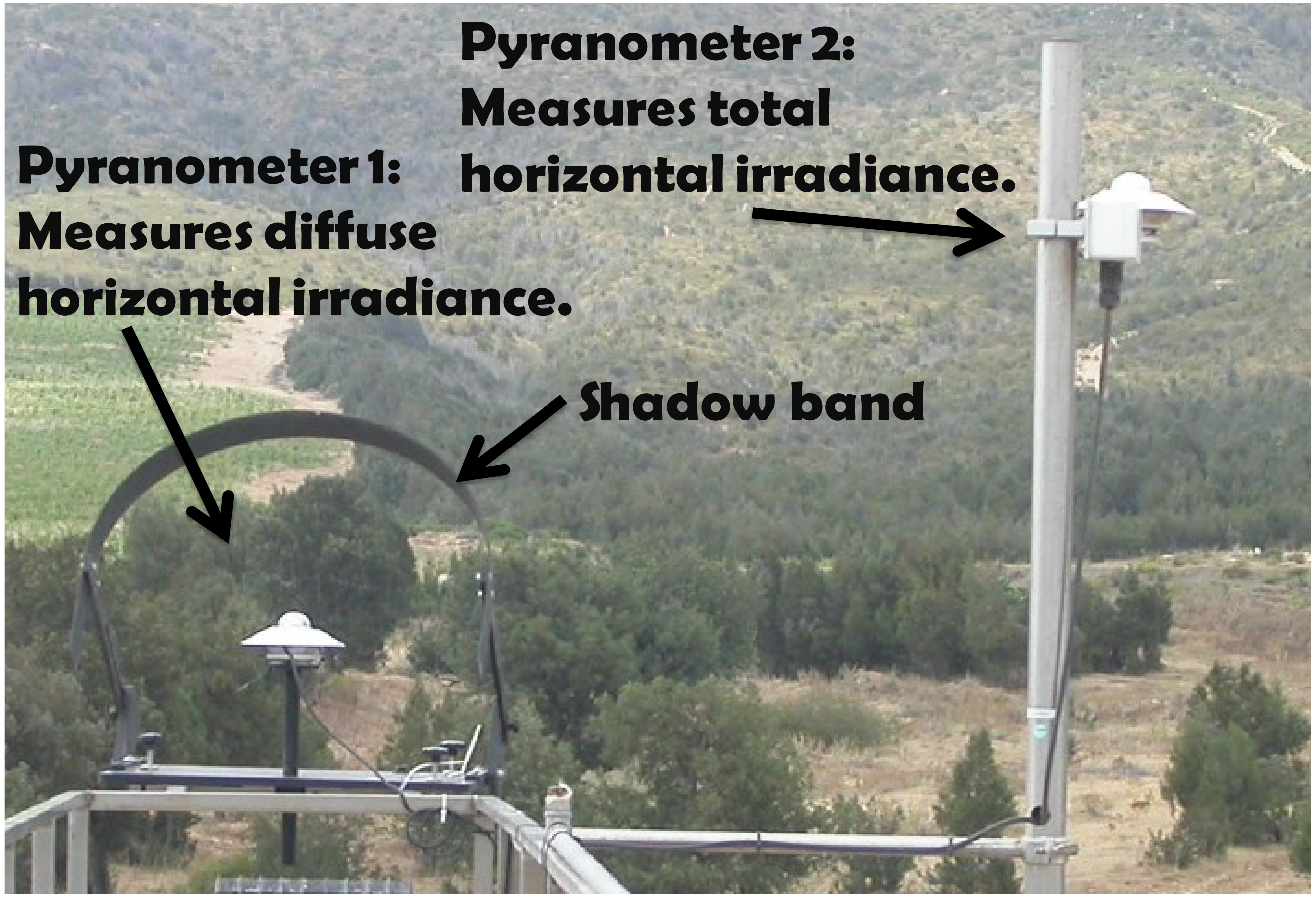
PHOTOVOLTAIC SENSOR

SPECTRORADIOMETER

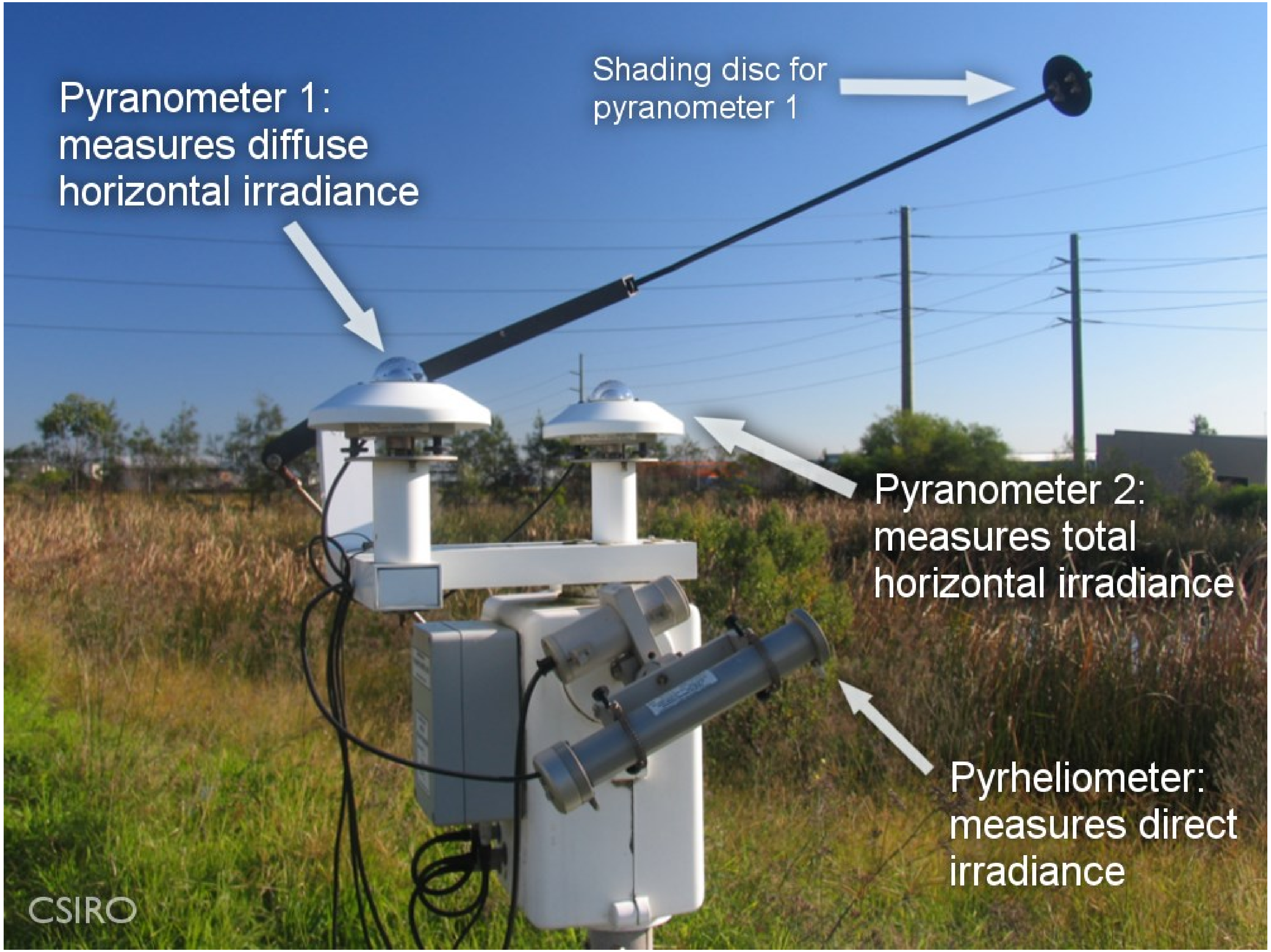
Iolographic
g Monochromator

Silicon Detector

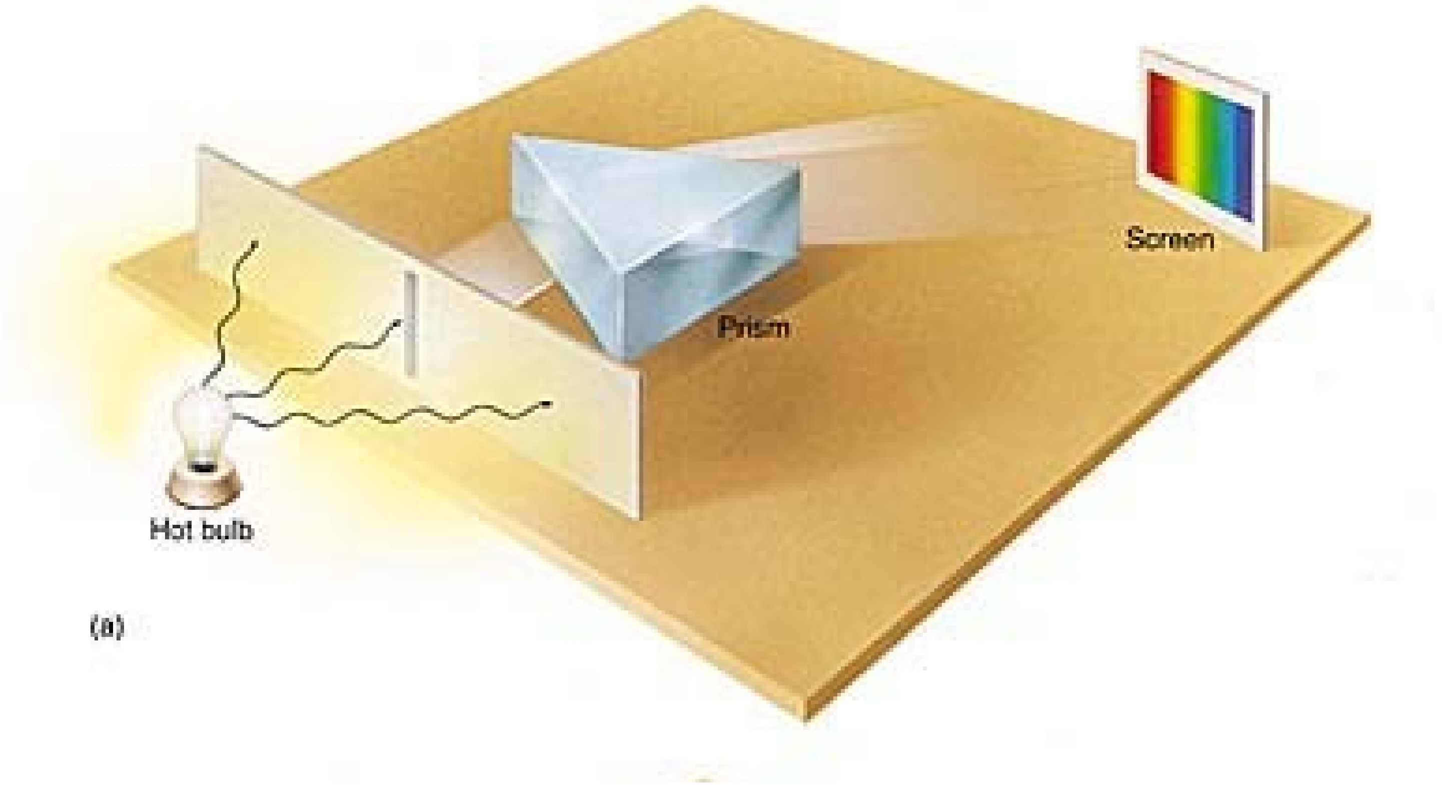
SPECTRORADIOMETER

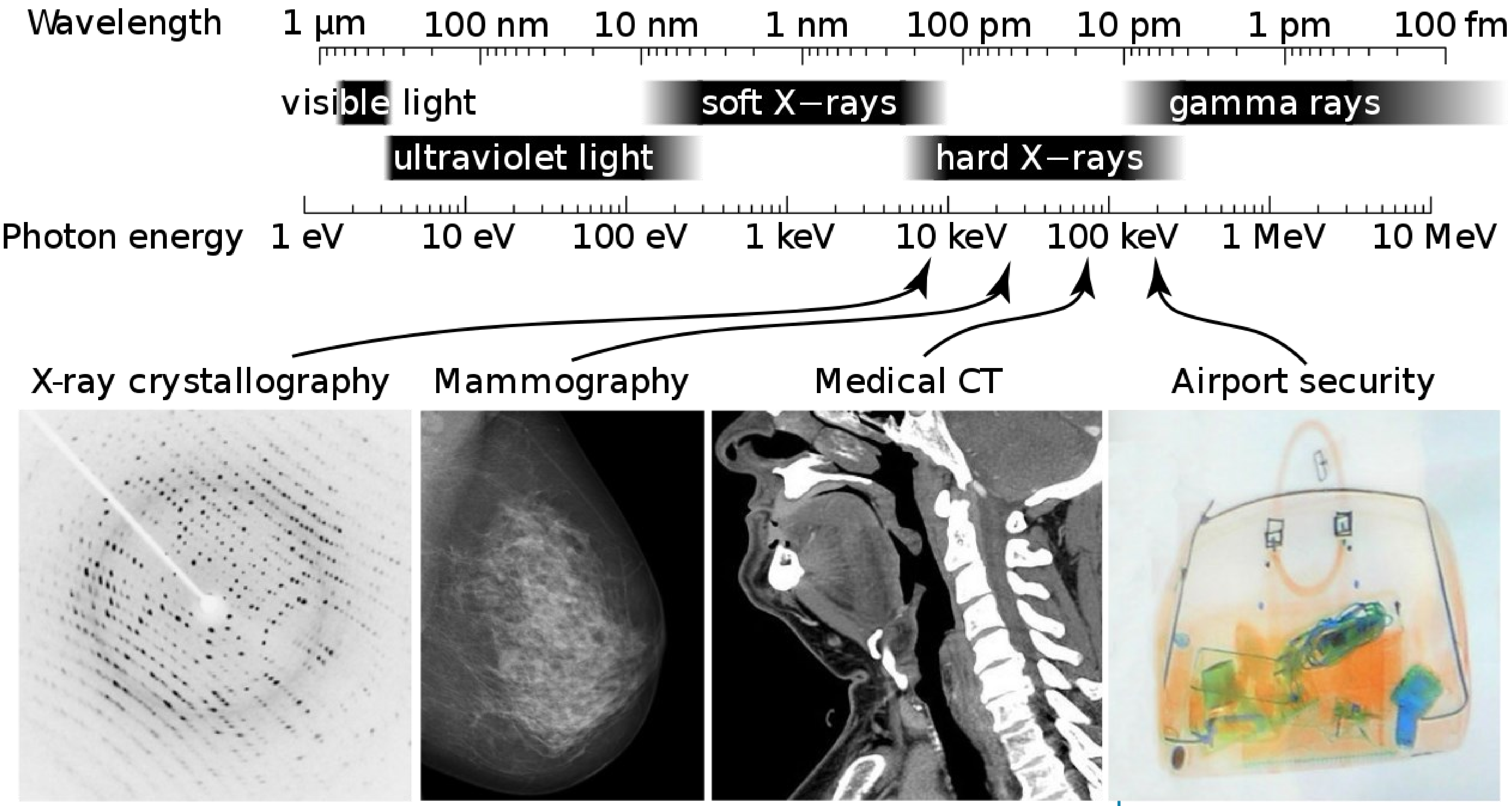

Pyranometer 2:
Measures total
horizontal irradiance.
Pyranometer 1:
Measures diffuse
horizontal irradiance.
Shadow band

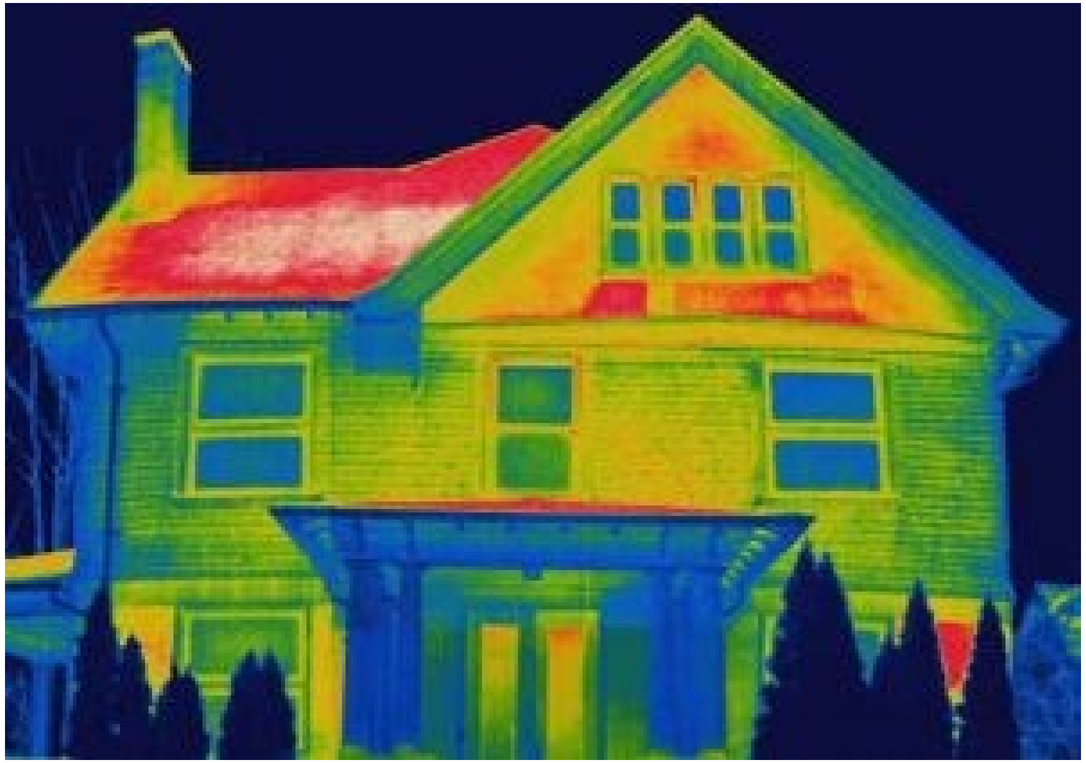
PYRHELIOMETER


Pyranometer 1:
measures diffuse
horizontal irradiance
Shading disc for
pyranometer 1
Pyranometer 2:
measures total
horizontal irradiance
Pyrheliometer:
measures direct
irradiance
CSIRO

SPECTRAL BLACKBODY EMISSIVE POWER

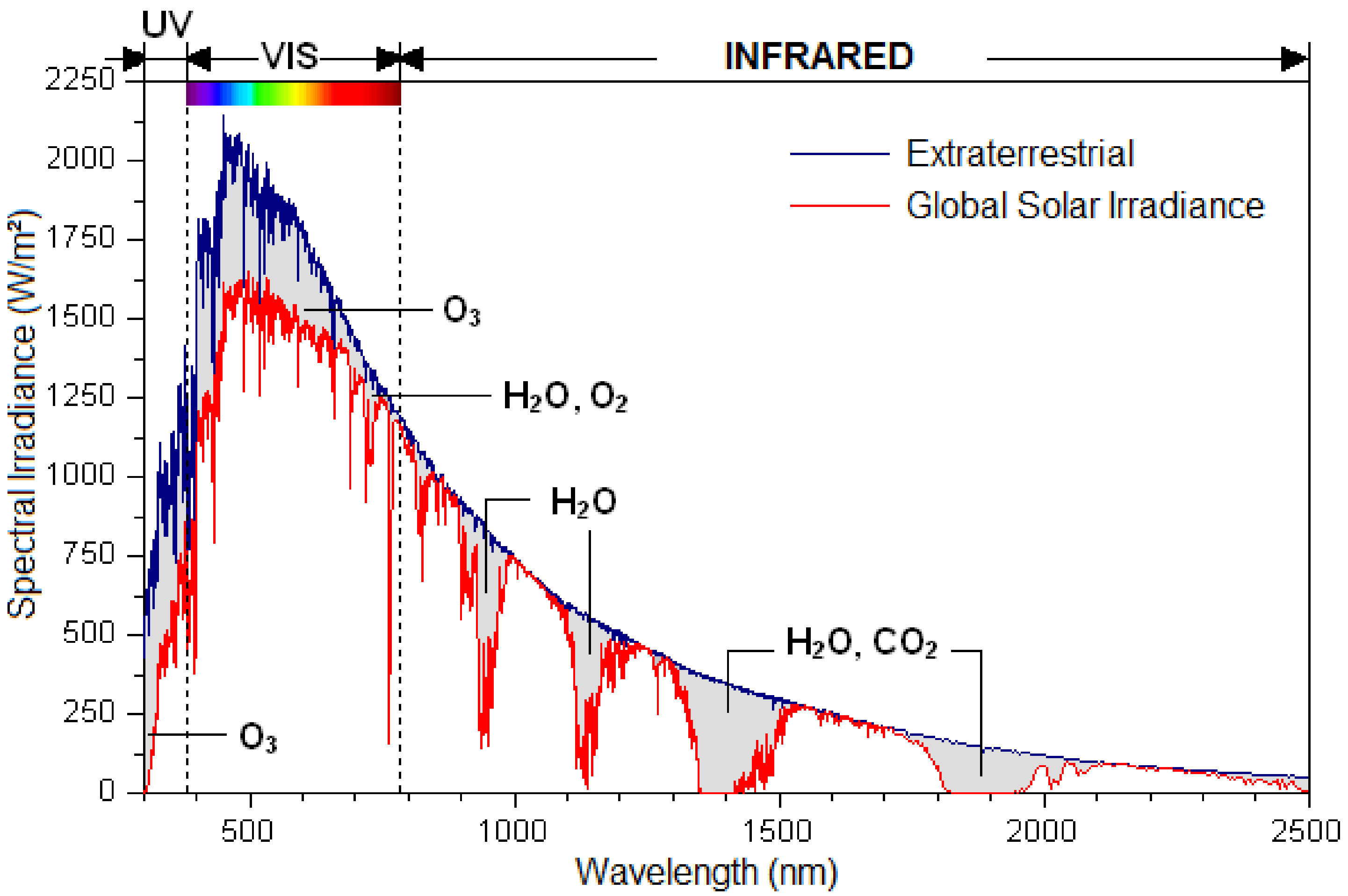



Wavelength
1 µm
100 nm
10 nm
1 nm
100 pm
10 pm
1 pm
100 fm
visible light
soft X−rays
gamma rays
ultraviolet light
hard X−rays
Photon energy
1 eV
10 eV
100 eV
1 keV
10 keV
100 keV
1 MeV
10 MeV
X-ray crystallography
Mammography
Medical CT
Airport security

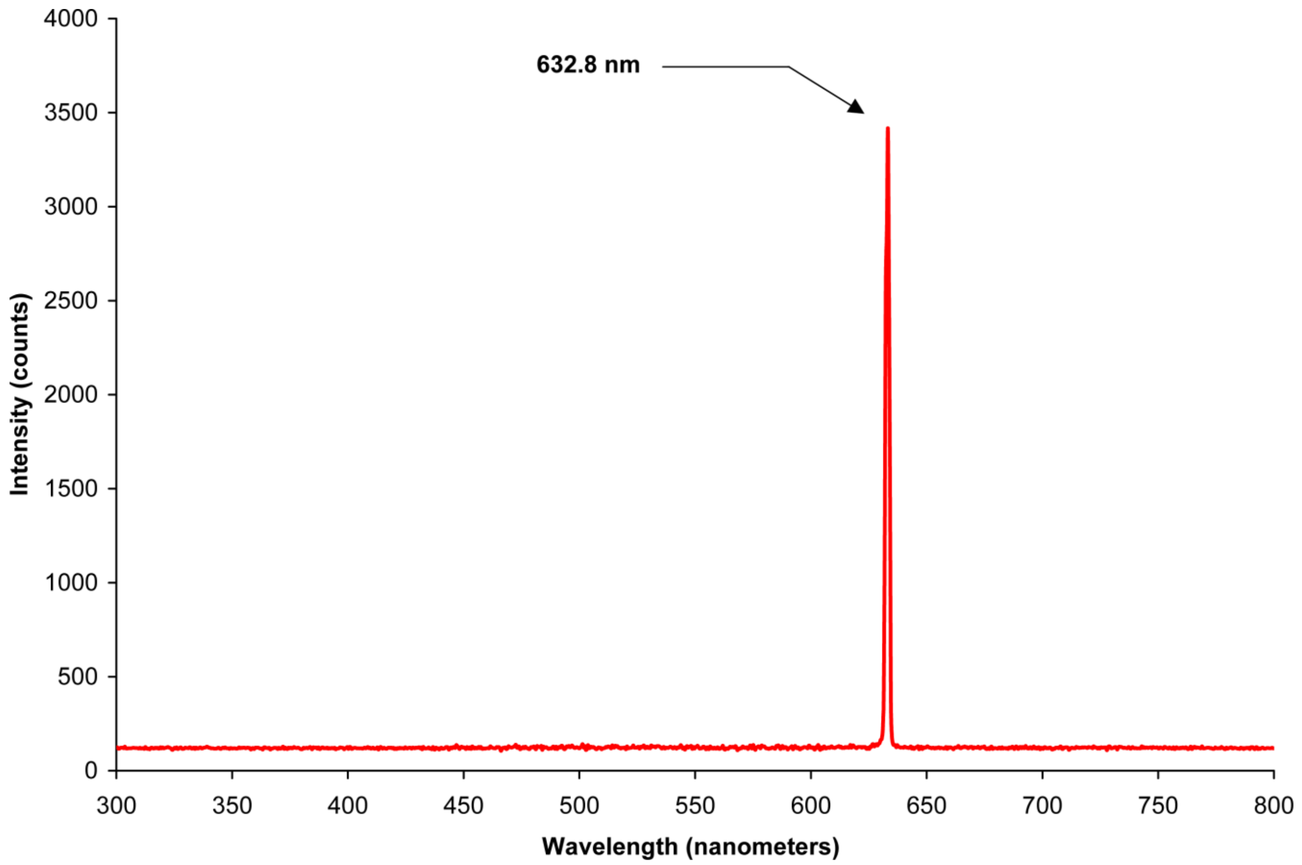


THERMAL CAMERA!!

SOLAR SPECTRUM



HELIUM NEON LASER SPECTRUM



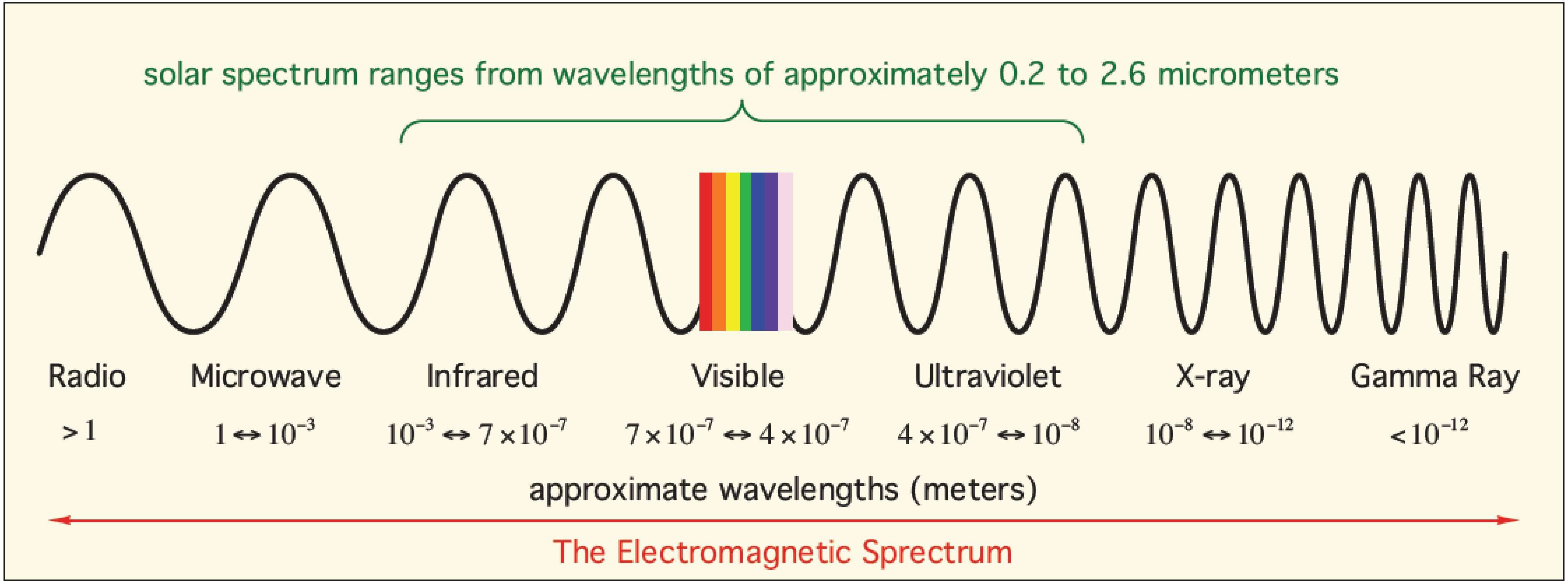
3. THE ELECTROMAGNETIC WAVES

Electromagnetic waves transport energy just like other waves, and all electromagnetic waves travel at the *speed of light* in a vacuum, which is

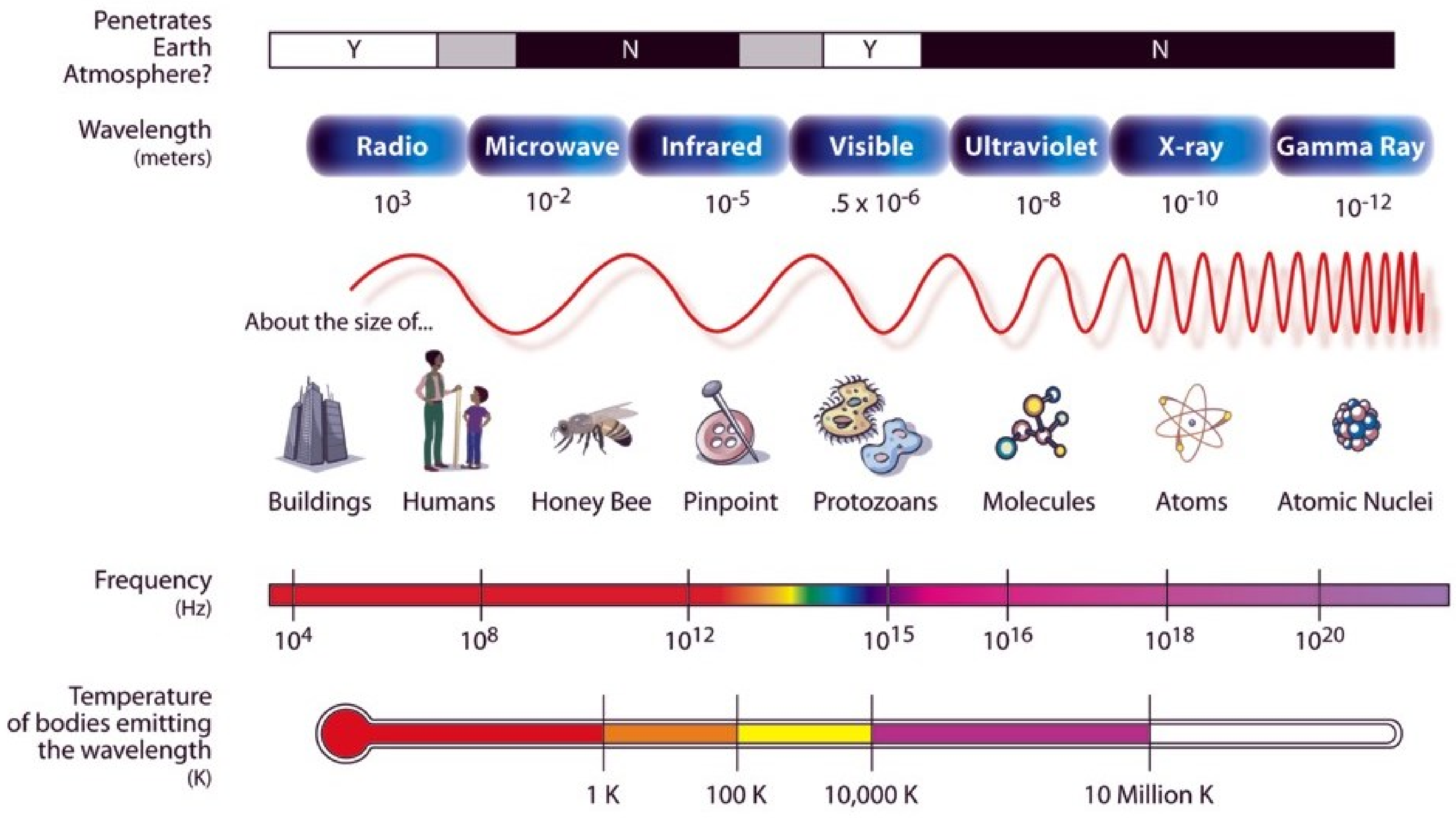
$C_0 = 2.9979\ \ 10^8$ m/s.

Electromagnetic waves are characterized by their *frequency* or *wavelength* .

$$\lambda = \frac{c}{\nu}$$


solar spectrum ranges from wavelengths of approximately 0.2 to 2.6 micrometers
Radio
Microwave
Infrared
Visible
Ultraviolet
X-ray
Gamma Ray
> 1
$1 \leftrightarrow 10^{-3}$
$10^{-3} \leftrightarrow 7 \times 10^{-7}$
$7 \times 10^{-7} \leftrightarrow 4 \times 10^{-7}$
$4 \times 10^{-7} \leftrightarrow 10^{-8}$
$10^{-8} \leftrightarrow 10^{-12}$
$< 10^{-12}$
approximate wavelengths (meters)
The Electromagnetic Sprectrum

3.A THE ELECTROMAGNETIC SPECTRUM



3.B PHOTON ENERGY

each photon of frequency ν is considered to have an energy of:

$$e = h\nu = \frac{hc}{\lambda}$$

h $=6.6256 \times 10^{-34}$ J · s is *Planck's constant*

The Energy of a photon is inversely proportional to its wavelength

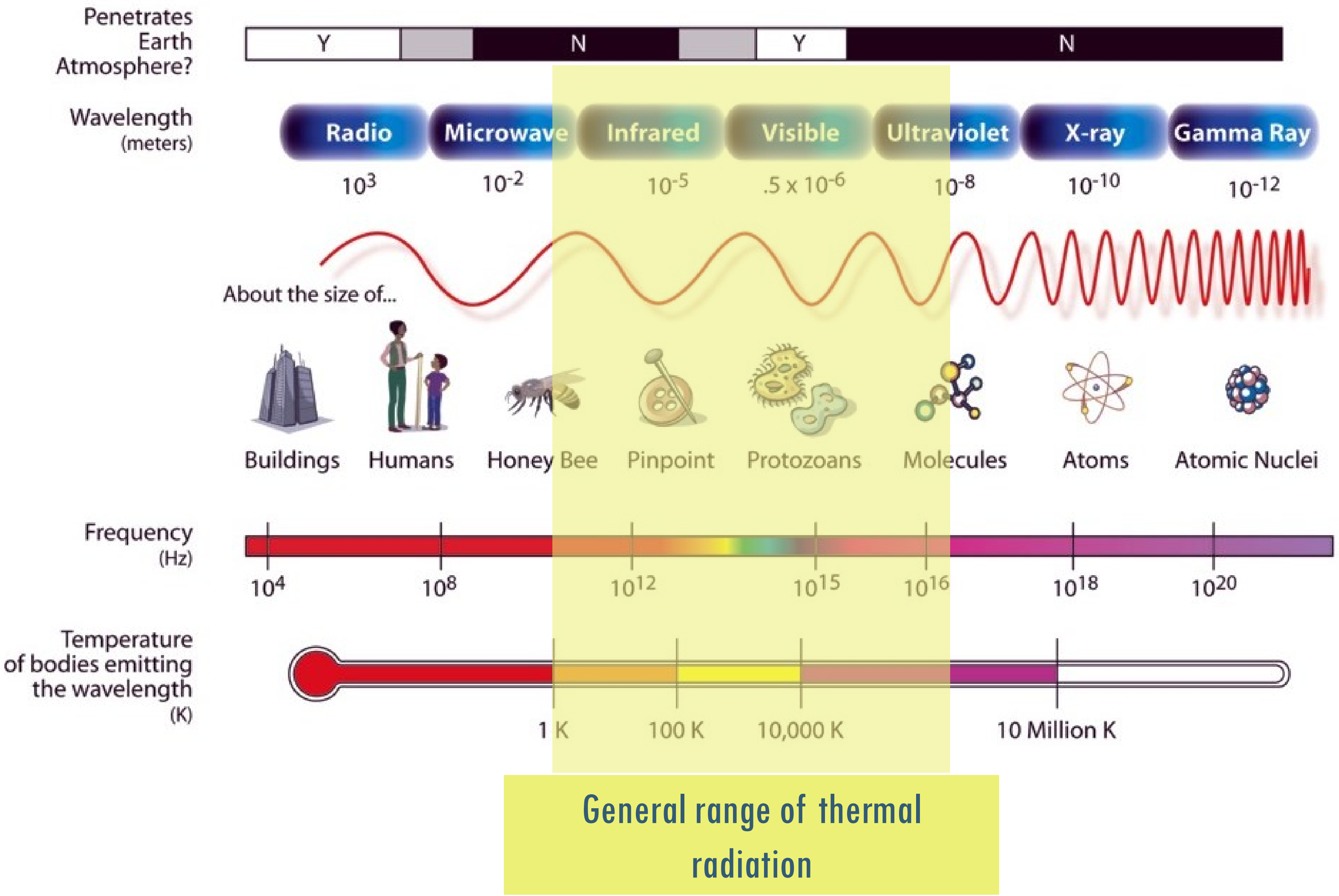
3.C THERMAL RADIATION

Thermal radiation emitted as a result of energy transitions of molecules, atoms, and electrons of a substance.

Thermal radiation is defined as the portion of the electromagnetic spectrum that extends from about 0.1 to 100 μm.

thermal radiation includes the entire visible and infrared (IR) radiation as well as a portion of the ultraviolet (UV) radiation.

3.C THERMAL RADIATION



light is simply the *visible* portion of the electromagnetic spectrum that lies between 0.40 and 0.76 μm.

Light, or the visible spectrum, consists of narrow bands of color from violet (0.40–0.44 μm) to red (0.63–0.76 μm)

A body that emits some radiation in the visible range is called a light source.

The sun is obviously our primary light source.

The electromagnetic radiation emitted by the sun is known as **solar radiation,** and nearly all of it falls into the wavelength band 0.3–3 μm.

3.D FUNDAMENTALS OF THERMAL RADIATION

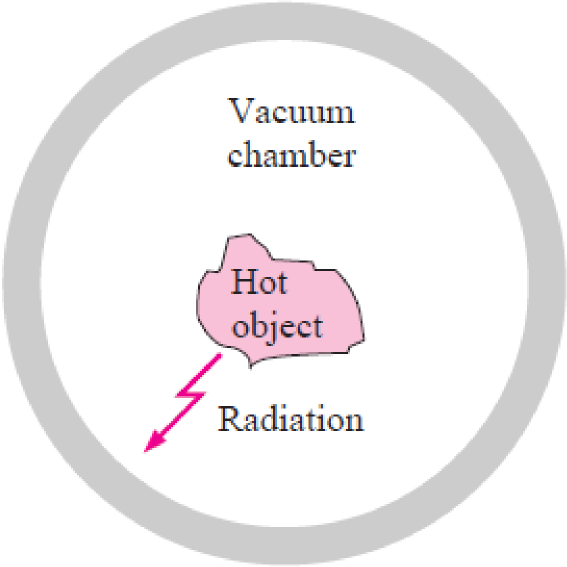


FIGURE 11–1
A hot object in a vacuum chamber loses heat by radiation only.

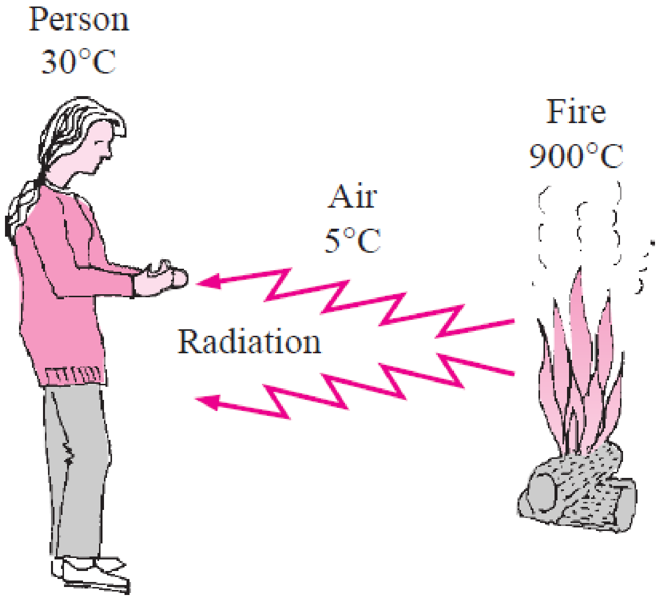


FIGURE 11–2
Unlike conduction and convection, heat transfer by radiation can occur between two bodies, even when they are separated by a medium colder than both of them.

3.d FUNDAMENTALS OF THERMAL RADIATION

Thermal radiation is continuously emitted by all matter whose temperature is above absolute zero.

“everything around us such as walls, furniture, and our friends constantly emits (and absorbs) radiation.”

3.E BLACKBODY RADIATION

The amount of radiation energy emitted from a surface at a given wavelength depends on the:

- material of the body
- the condition of its surface
- the surface temperature.

- A **blackbody** is defined as a perfect emitter and absorber of radiation.

E_B "*TOTAL* BLACKBODY EMISSIVE POWER"

The radiation energy emitted by a blackbody per unit time and per unit surface area was determined experimentally by Joseph Stefan in 1879 and expressed as:

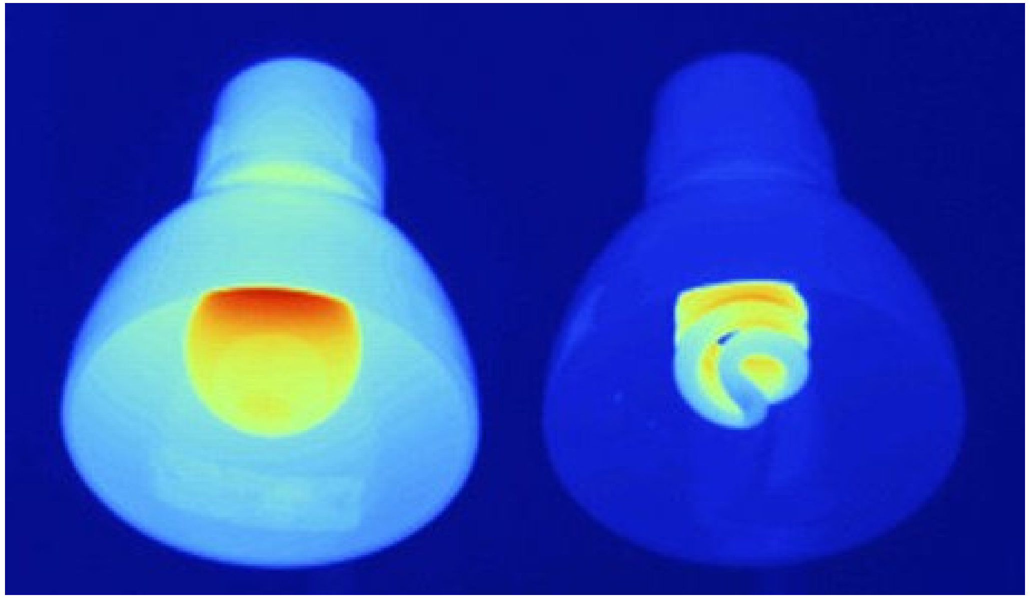
$$E_b(T) = \sigma T^4 \qquad (\text{W/m}^2)$$

E_b is the *total* blackbody emissive power, which is the sum of the radiation emitted over all wavelengths.

$\sigma = 5.67 \times 10^{-8}\ \text{W/m}^2 \cdot \text{K}^4$ is the *Stefan–Boltzmann constant*

$E_{b\lambda}$ SPECTRAL BLACKBODY EMISSIVE POWER

the amount of radiation energy emitted by a blackbody at an absolute temperature T per unit time, per unit surface area, and per unit wavelength about the wavelength λ.



SPECTRAL BLACKBODY EMISSIVE POWER

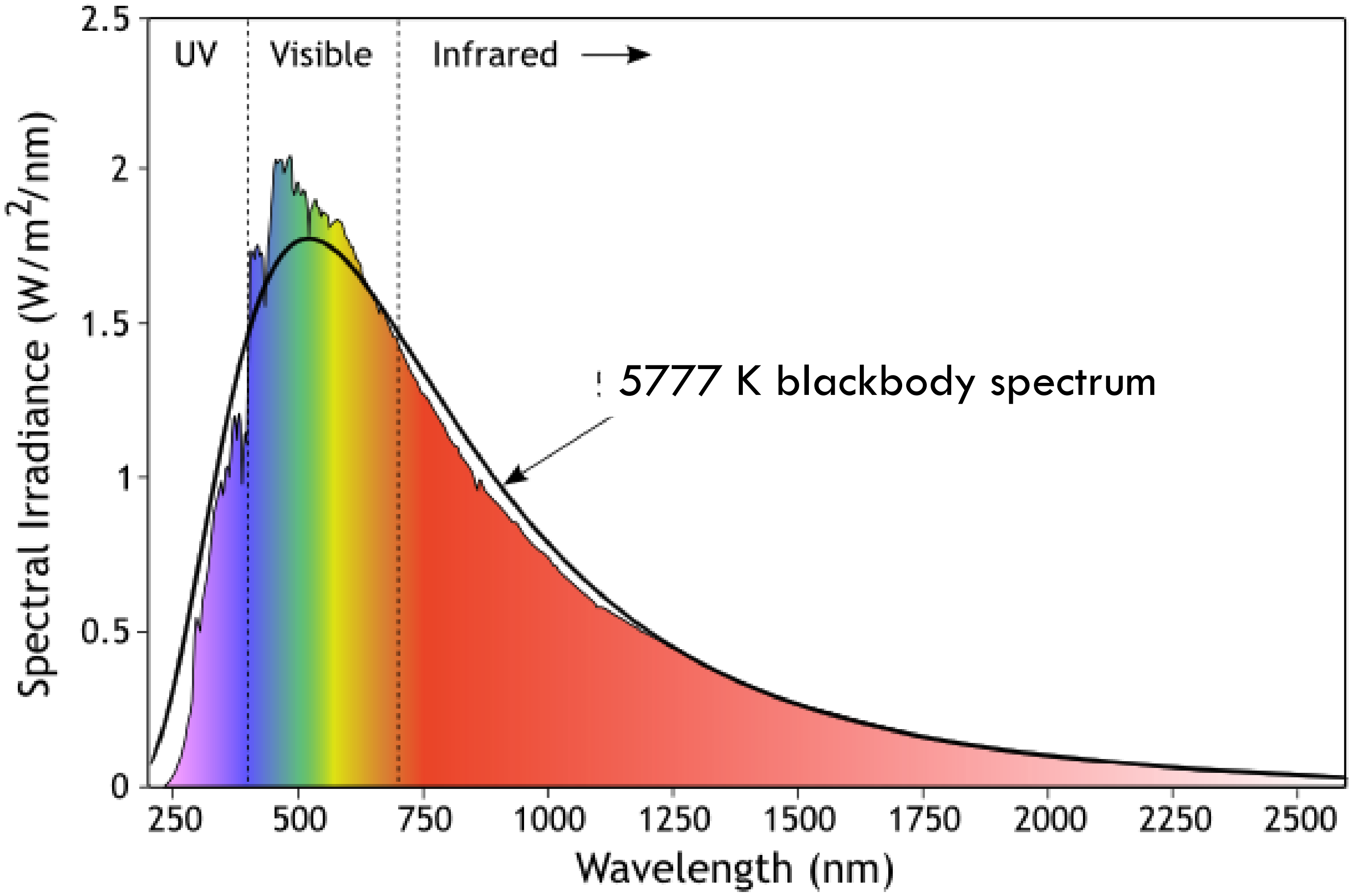
The relation for the spectral blackbody emissive power $E_{b\lambda}$ was developed by Max Planck in 1901 in conjunction with his famous quantum theory.

This relation is known as **Planck's law** and is expressed as

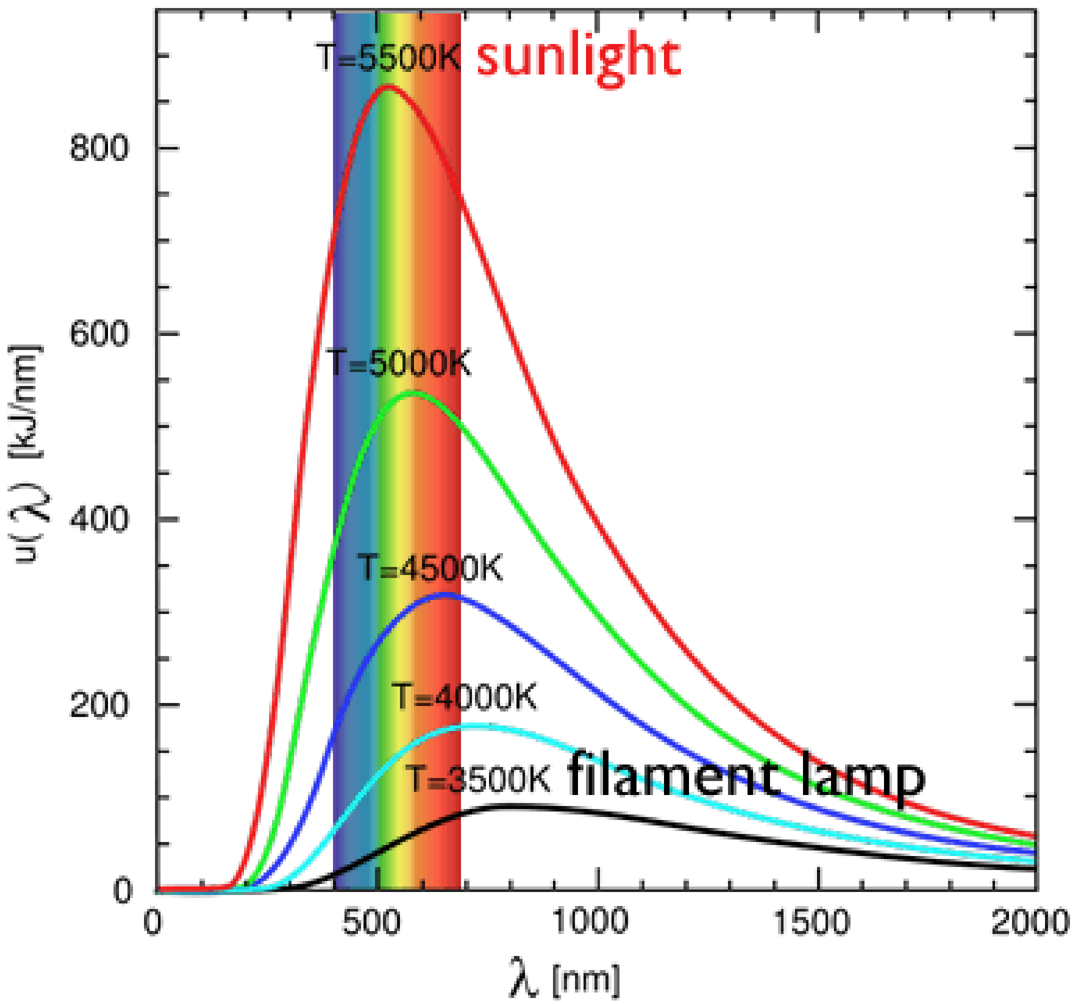
$$E_{b\lambda}(\lambda, T) = \frac{C_1}{\lambda^5[\exp(C_2/\lambda T) - 1]} \qquad (\mathrm{W/m^2 \cdot \mu m})$$

$$C_1 = 2\pi h c_0^2 = 3.742 \times 10^8 \ \mathrm{W \cdot \mu m^4/m^2}$$

$$C_2 = h c_0/k = 1.439 \times 10^4 \ \mathrm{\mu m \cdot K}$$

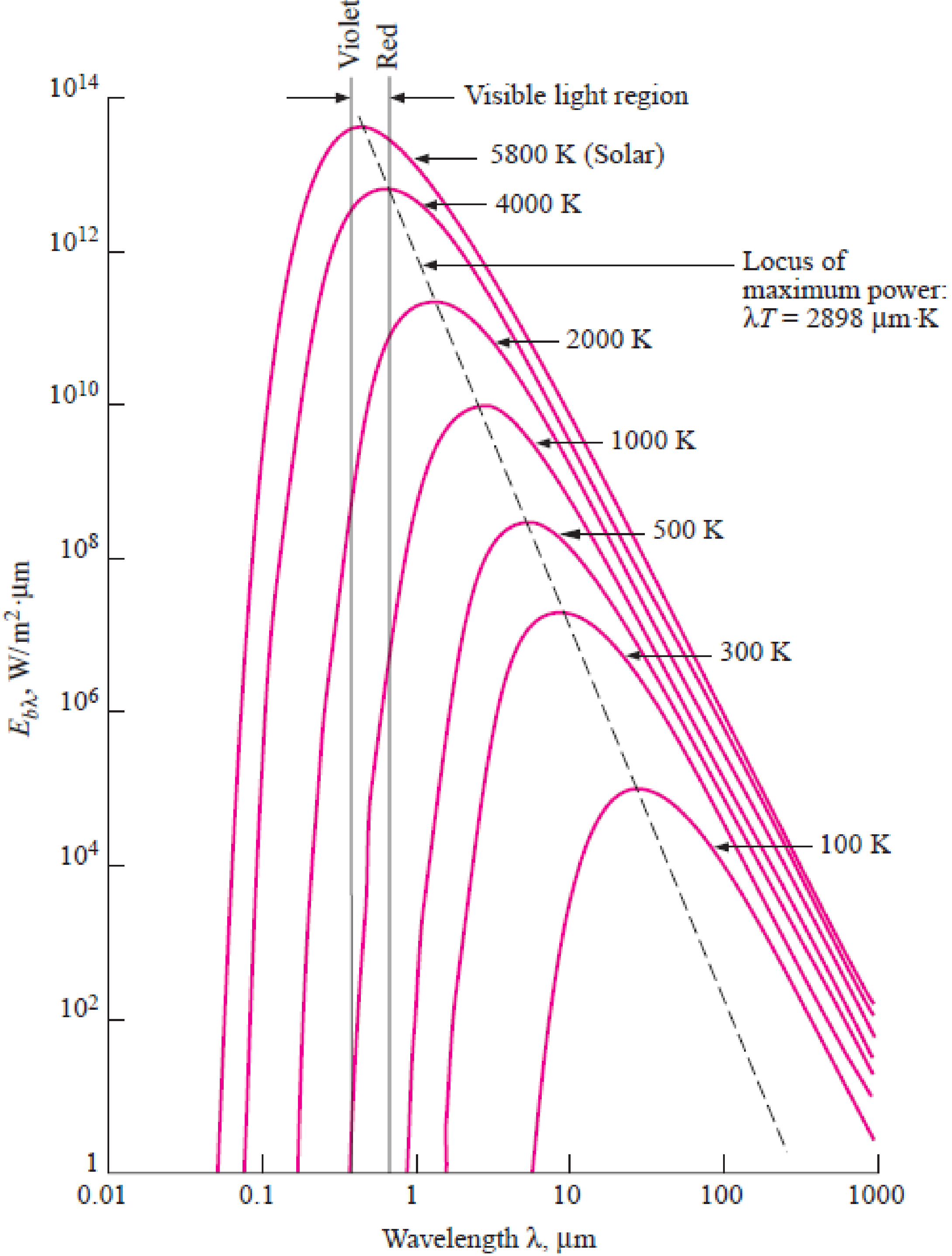


UV
Visible
Infrared
5777 K blackbody spectrum
Spectral Irradiance (W/m2/nm)
Wavelength (nm)
2.5
2
1.5
1
0.5
0
250
500
750
1000
1250
1500
1750
2000
2250
2500



sunlight
T=5500K
T=5000K
T=4500K
T=4000K
T=3500K
filament lamp
u(λ) [kJ/nm]
λ [nm]
0
200
400
600
800
500
1000
1500
2000

The variation of the blackbody emissive power with wavelength for several temperatures.

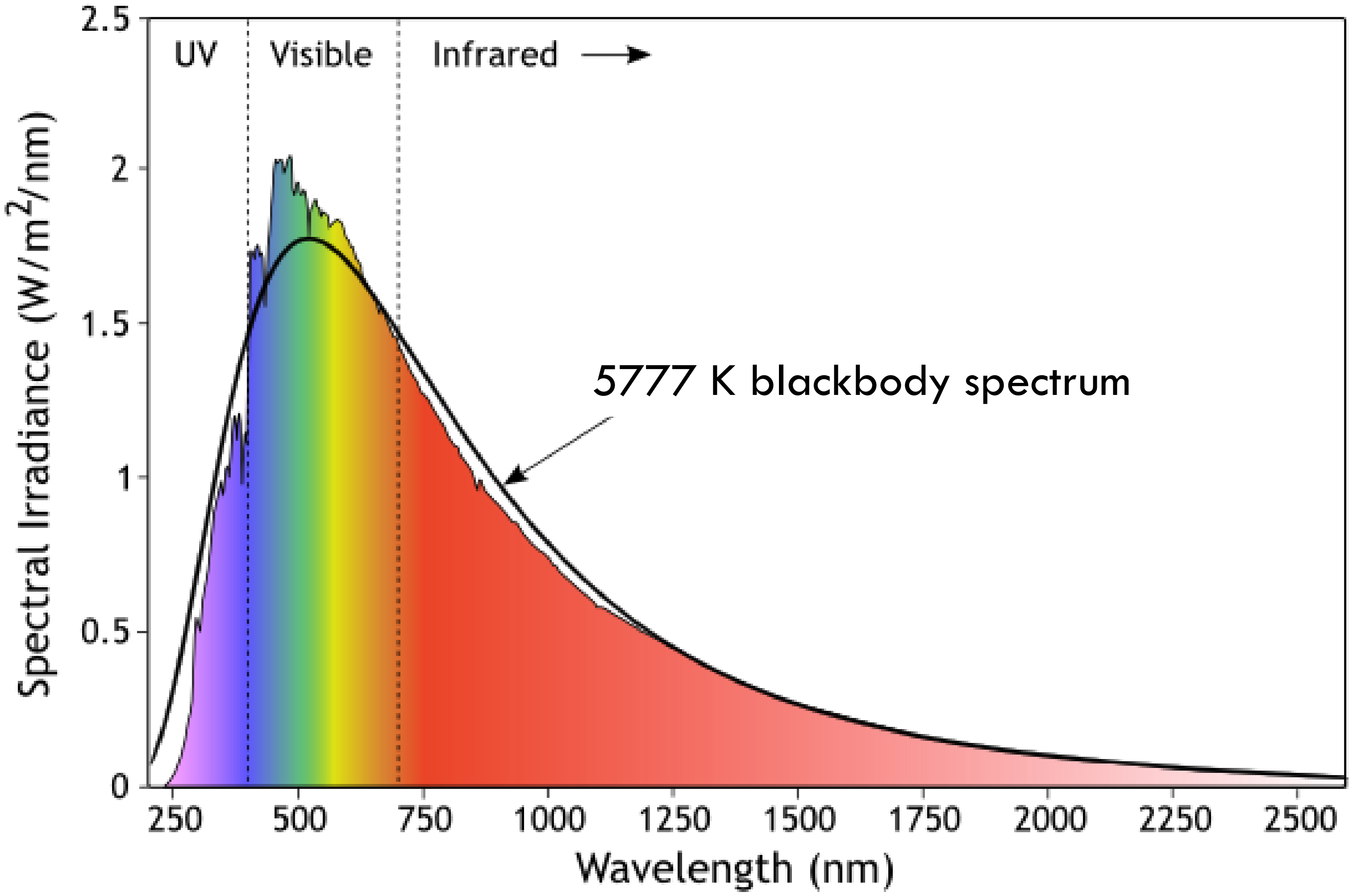


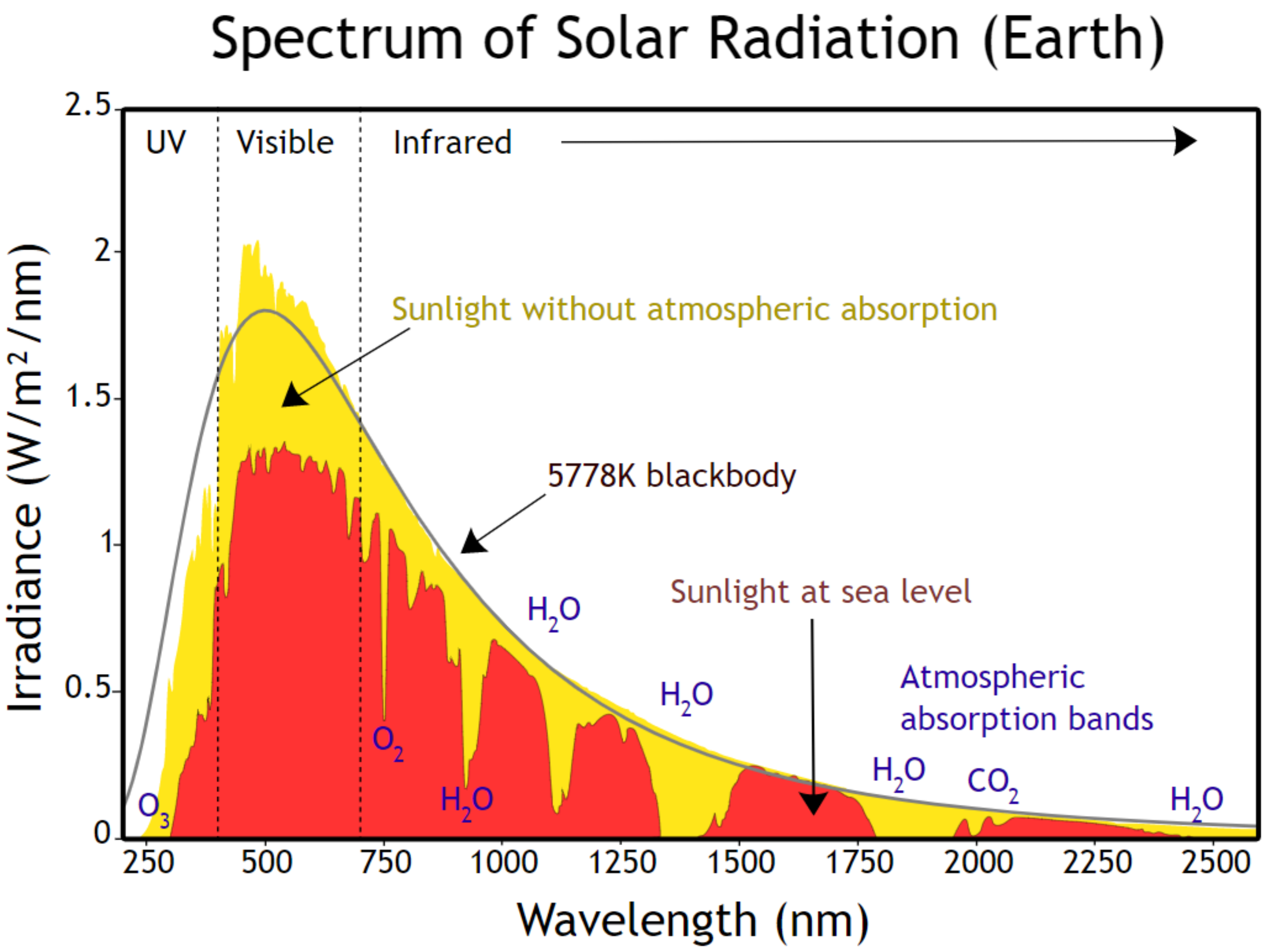
As the temperature increases, the peak of the curve shifts toward shorter wavelengths. The wavelength at which the peak occurs for a specified temperature is given by **Wien's displacement law** as

$$(\lambda T)_{\text{max power}} = 2897.8\ \mu\text{m} \cdot \text{K}$$

The peak of the solar radiation, for example, occurs at $\lambda = 2897.8/5780 = 0.50\ \mu\text{m}$, which is near the middle of the visible range. The peak of the radiation emitted by a surface at room temperature ($T = 298$ K) occurs at $9.72\ \mu\text{m}$, which is well into the infrared region of the spectrum.

SOLAR SPECTRUM IN COMPARISON TO THE SPECTRUM OF A BLACK RADIATOR AT 5777K





Spectrum of Solar Radiation (Earth)
UV
Visible
Infrared
Sunlight without atmospheric absorption
5778K blackbody
Sunlight at sea level
Atmospheric absorption bands
O_3
O_2
H_2O
H_2O
H_2O
H_2O
CO_2
H_2O
Irradiance ($W/m^2/nm$)
Wavelength (nm)
0
0.5
1
1.5
2
2.5
250
500
750
1000
1250
1500
1750
2000
2250
2500

SPECTRAL DISTRIBUTION OF EXTRATERRESTRIAL RADIATION

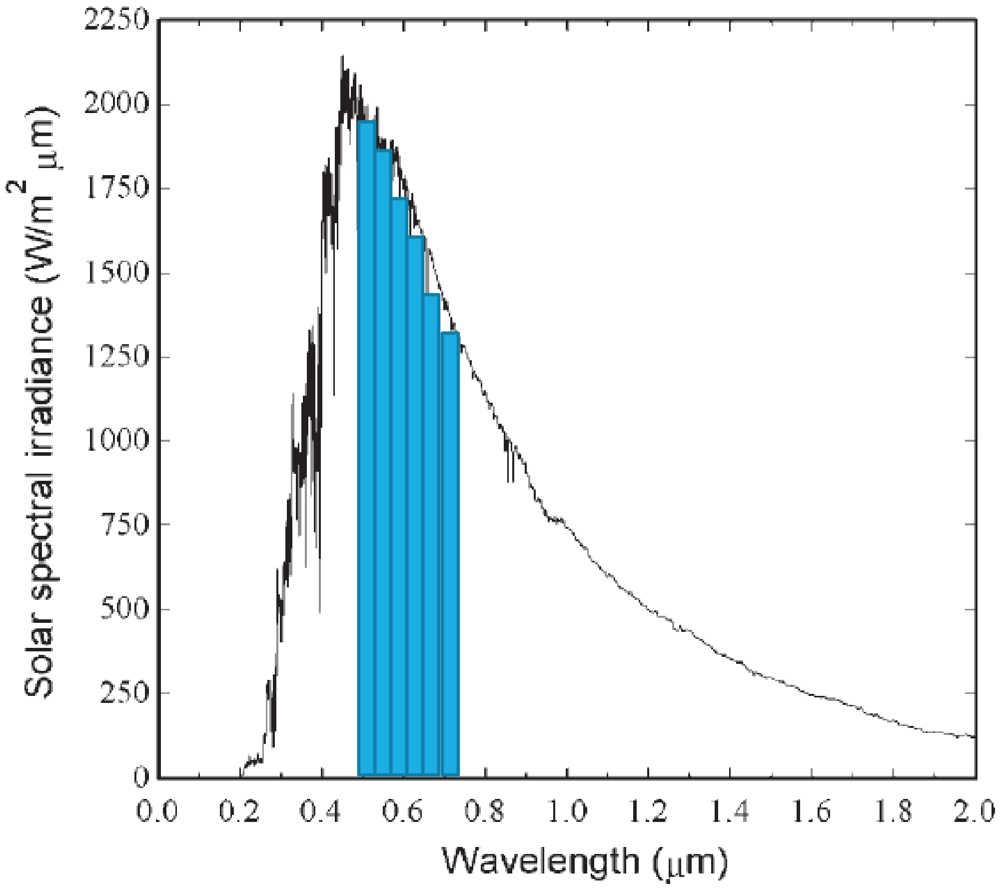


Figure 1.3.1 The WRC standard spectral irradiance curve at mean earth-sun distance.

Table 1.3.1a Extraterrestrial Solar Irradiance (WRC Spectrum) in Increments of Wavelength[a]

λ (μm)	$G_{sc,\lambda}$ (W/m^2 μm)	$f_{0-\lambda}$ (−)	λ (μm)	$G_{sc,\lambda}$ (W/m^2 μm)	$f_{0-\lambda}$ (−)	λ (μm)	$G_{sc,\lambda}$ (W/m^2 μm)	$f_{0-\lambda}$ (−)
0.250	81.2	0.001	0.520	1849.7	0.243	0.880	955.0	0.622
0.275	265.0	0.004	0.530	1882.8	0.257	0.900	908.9	0.636
0.300	499.4	0.011	0.540	1877.8	0.271	0.920	847.5	0.648
0.325	760.2	0.023	0.550	1860.0	0.284	0.940	799.8	0.660
0.340	955.5	0.033	0.560	1847.5	0.298	0.960	771.1	0.672
0.350	955.6	0.040	0.570	1842.5	0.312	0.980	799.1	0.683
0.360	1053.1	0.047	0.580	1826.9	0.325	1.000	753.2	0.695
0.370	1116.2	0.056	0.590	1797.5	0.338	1.050	672.4	0.721
0.380	1051.6	0.064	0.600	1748.8	0.351	1.100	574.9	0.744
0.390	1077.5	0.071	0.620	1738.8	0.377	1.200	507.5	0.785
0.400	1422.8	0.080	0.640	1658.7	0.402	1.300	427.5	0.819
0.410	1710.0	0.092	0.660	1550.0	0.425	1.400	355.0	0.847
0.420	1687.2	0.105	0.680	1490.2	0.448	1.500	297.8	0.871
0.430	1667.5	0.116	0.700	1413.8	0.469	1.600	231.7	0.891
0.440	1825.0	0.129	0.720	1348.6	0.489	1.800	173.8	0.921
0.450	1992.8	0.143	0.740	1292.7	0.508	2.000	91.6	0.942
0.460	2022.8	0.158	0.760	1235.0	0.527	2.500	54.3	0.968
0.470	2015.0	0.173	0.780	1182.3	0.544	3.000	26.5	0.981
0.480	1975.6	0.188	0.800	1133.6	0.561	3.500	15.0	0.988
0.490	1940.6	0.202	0.820	1085.0	0.578	4.000	7.7	0.992
0.500	1932.2	0.216	0.840	1027.7	0.593	5.000	2.5	0.996
0.510	1869.1	0.230	0.860	980.0	0.608	8.000	1.0	0.999

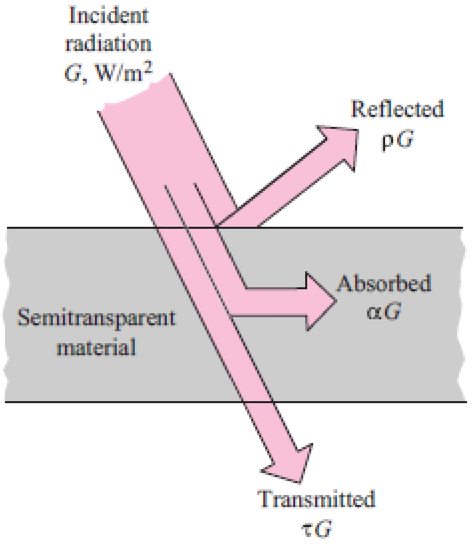
[a] $G_{sc,\lambda}$ is the average solar irradiance over the interval from the middle of the preceding wavelength interval to the middle of the following wavelength interval. For example, at 0.600 μm. 1748.8 W/m^2 μm is the average value between 0.595 and 0.610 μm.

Calculate the fraction of the extraterrestrial solar radiation and the amount of that radiation in the ultraviolet ($\lambda < 0.38\ \mu$m), the visible ($0.38\ \mu\text{m} < \lambda < 0.78\ \mu$m), and the infrared ($\lambda > 0.78\ \mu$m) portions of the spectrum.

From Table 1.3.1a, the fractions of $f_{0-\lambda}$ corresponding to wavelengths of 0.38 and 0.78 μm are 0.064 and 0.544. Thus, the fraction in the ultraviolet is 0.064, the fraction in the visible range is $0.544 - 0.064 = 0.480$, and the fraction in the infrared is $1.0 - 0.544 = 0.456$. Applying these fractions to a solar constant of 1367 W/m^2 and tabulating the results, we have:

Wavelength range (μm)	0–0.38	0.38–0.78	0.78–∞
Fraction in range	0.064	0.480	0.456
Energy in range (W/m^2)	87	656	623

■



Absorptivity: $$\alpha = \frac{\text{Absorbed radiation}}{\text{Incident radiation}} = \frac{G_{abs}}{G}, \quad 0 \leq \alpha \leq 1 \qquad \text{(11-37)}$$

Reflectivity: $$\rho = \frac{\text{Reflected radiation}}{\text{Incident radiation}} = \frac{G_{ref}}{G}, \quad 0 \leq \rho \leq 1 \qquad \text{(11-38)}$$

Transmissivity: $$\tau = \frac{\text{Transmitted radiation}}{\text{Incident radiation}} = \frac{G_{tr}}{G}, \quad 0 \leq \tau \leq 1 \qquad \text{(11-39)}$$

$$\alpha + \rho + \tau = 1$$

For opaque surfaces, $\tau = 0$, and thus $\alpha + \rho = 1$

The Greenhouse Effect

Glass has a transparent window in the wavelength range 0.3 μm < λ < 3 μm in which over 90% of solar radiation is emitted. The entire radiation emitted by surfaces at room temperature falls in the infrared region (λ > 3 μm).

Glass allows the solar radiation to enter but does not allow the infrared radiation from the interior surfaces to escape. This causes a rise in the interior temperature as a result of the energy buildup in the car.

This heating effect, which is due to the nongray characteristic of glass (or clear plastics), is known as the **greenhouse effect**.

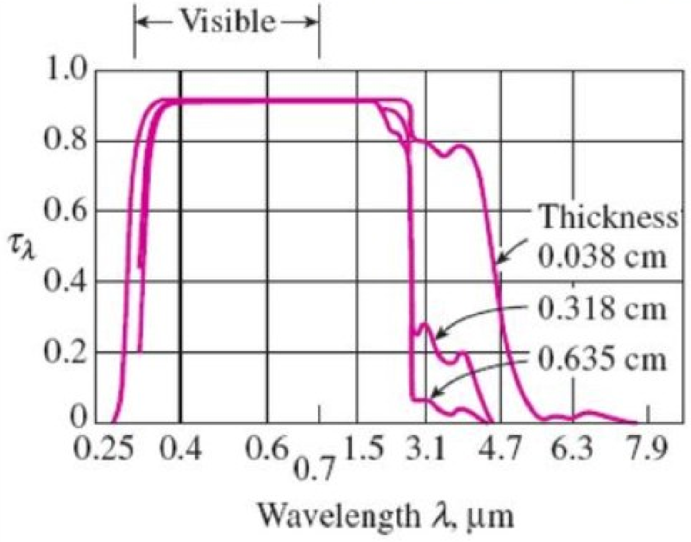


FIGURE 12–36
The spectral transmissivity of low-iron glass at room temperature for different thicknesses.

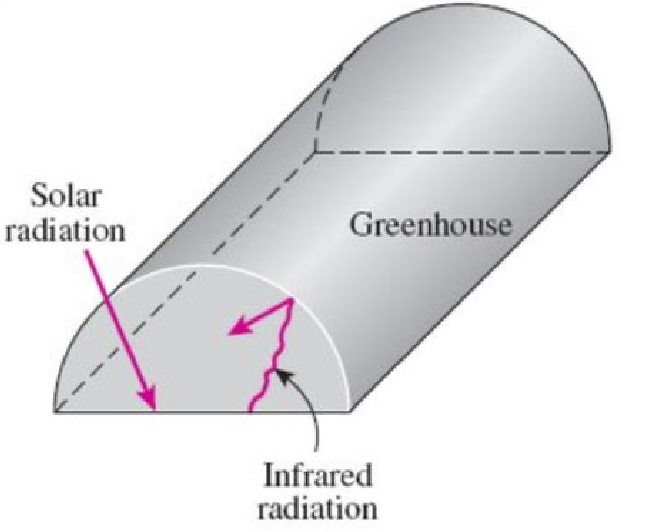


FIGURE 12–37
A greenhouse traps energy by allowing the solar radiation to come in but not allowing the infrared radiation to go out.

THANKS FOR YOUR ATTENTION

ANY QUESTIONS