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Properties of Solar Energy

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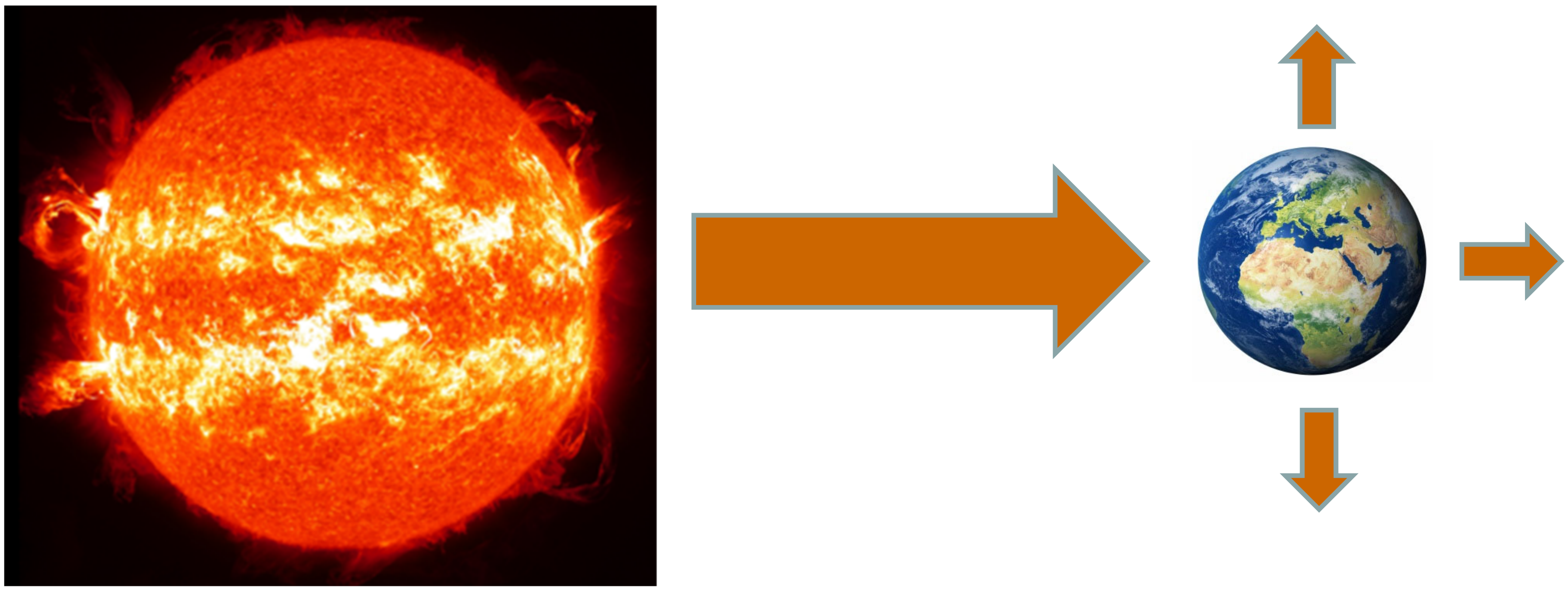
1. Solar properties



Basic units on Energy

Energy (J) = Work done (Force x distance, Nm) = Power x time (W x s)

$$\delta W = \vec{F} \cdot d\vec{S} = p \cdot dV$$

Work = Energy:

1 J (Julio) = 1 Nm (Newton x metro) = 1 Ws (Watt x second) = 0.2388 cal ≈ 0.24 cal

1 kWh = 860 kcal = 3,600 kJ

1 tep (tone oil equivalent toe) = 11,63 MWh

Power: work per time unit

$$\dot{W} = \frac{\delta W}{dt}$$

1 W = 1 J/s

1 CV (vapour horse, SI) ≈ 735 W

≈ 0.986 HP (horse power)

Power (production capacity)	
kW kilowatt	= 10^3 W
MW Megawatt	= 10^6 W
GW Gigawatt	= 10^9 W
TW Terawatt	= 10^{12} W
PW Pentawatt	= 10^{15} W
EW Exawatt	= 10^{18} W

Installed power: the capacity to produce energy, the measurement unit is W (kW, MW, GW)

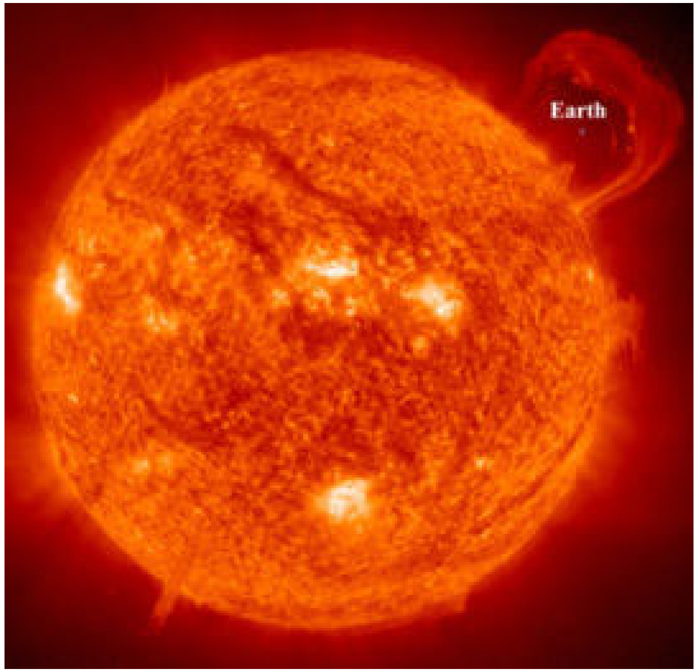
Energy production: kWh, MWh, GWh

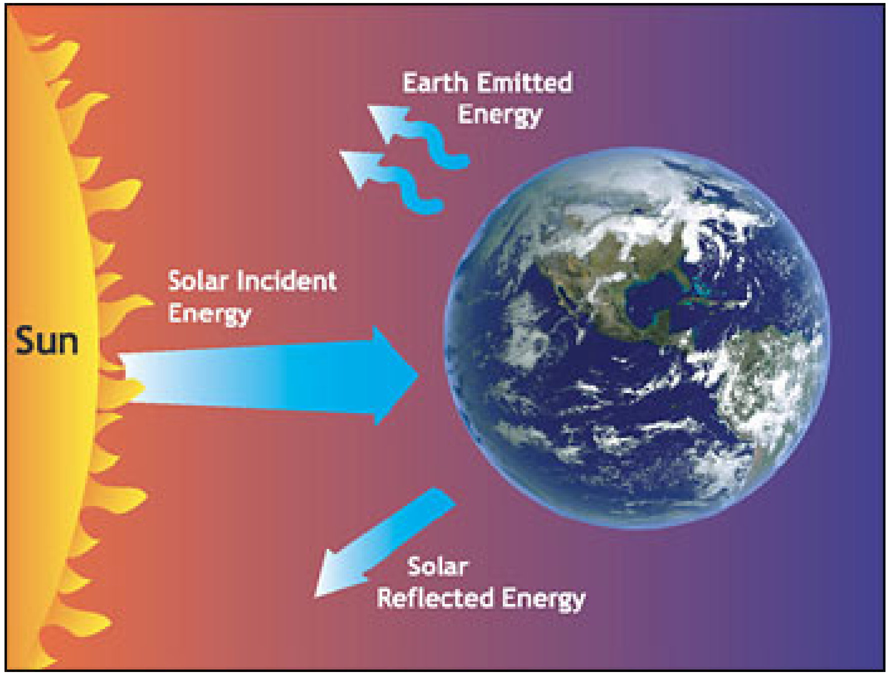
light bulb 100 W (discontinued) consume =>
per year (8760 h/year) 876 kWh
=> 876kWh-year ≈ 1,000 kWh-year = 1MWh-año

Energy from the Sun

Energy inputs:

Solar Radiation – Distance -Atmosphere





Energy depends on:

Emission Law: Stefan-Boltzmann Law

Energy distribution: Planck Law

Sun Radiation

Sun Photosphere temperature 5.785 ºK (5.800),
Sun Black body =>
=> electromagnetic radiation Stefan-Boltzmann Law.
Josef Stefan (1835 - 1893) y Ludwig Boltzmann (1844 - 1906)

$$E = \varepsilon \cdot \sigma \cdot T^4$$

$\sigma = 5.669 \times 10^{-8}$ Wm^{-2} $°K^{-4}$ Stefan-Boltzmann constant
ε emissivity (black body, $\varepsilon = 1$, general $\varepsilon \leq 1$)

Sun surface emission
assuming black body: $E = 6.35 \times 10^{7}$ Wm^{-2}

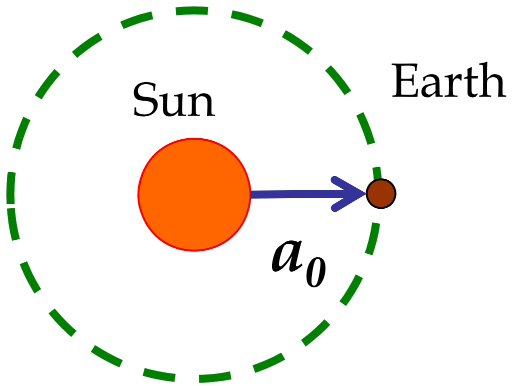
Total Sun Emission.
Sun radius, r_s, 6.959×10^{8} m,
$As=4\pi r_s^2$

$E_S = E * A_S = 3.873 \times 10^{26}$ W

Solar Irradiance: energy received from Sun

Total Sun Emission.

$$L_s = 4 \cdot \pi \cdot r_s^2 \cdot \sigma \cdot T^4 = 3.65 \cdot 10^{26} W$$



Solar emission sphere $S = 4 \cdot \pi \cdot a_0^2$

Irradiance: solar radiation in the top of the atmosphere

$$I_{SC} = S_0 = \frac{L_s}{S} = \sigma \cdot T_S^4 \cdot \left(\frac{r_s}{a_0} \right)^2 = 1366 \frac{W}{m^2}$$ Solar constant

Ts = 5.776 K sun temperature
r_s Sun radius: 6.959 x 10^8 m
a_0 Sun-Earth distance (1 UA, 149.597.871 km, irradiance arrives in 8 min y 19 s)
σ Stefan-Boltzmann constant (4.903 10^{-9} MJ m^{-2} K^{-4} day^{-1})

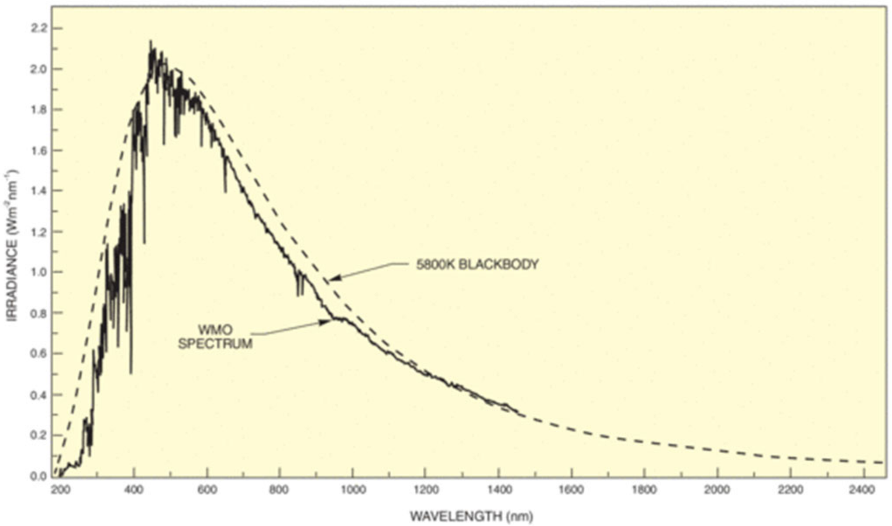
Planck Law. Irradiance distribution

Spectral distribution wavelenght, λ, Planck's Law
German physic Max Planck (1858 - 1947)

$$E_\lambda = \frac{C_1}{\lambda^5 \cdot \left(e^{\frac{C_2}{\lambda T}} - 1 \right)}$$

$c_1 = 2\pi h c^2$ $\qquad$ $c_2 = hc/k_B$.

first radiation constant c_{1L} and the **second radiation constant** c_2
h Planck constant => h = 6,62606957(29) ×10 -34 J×s



Speed of light
c = 299,792,458 m/s

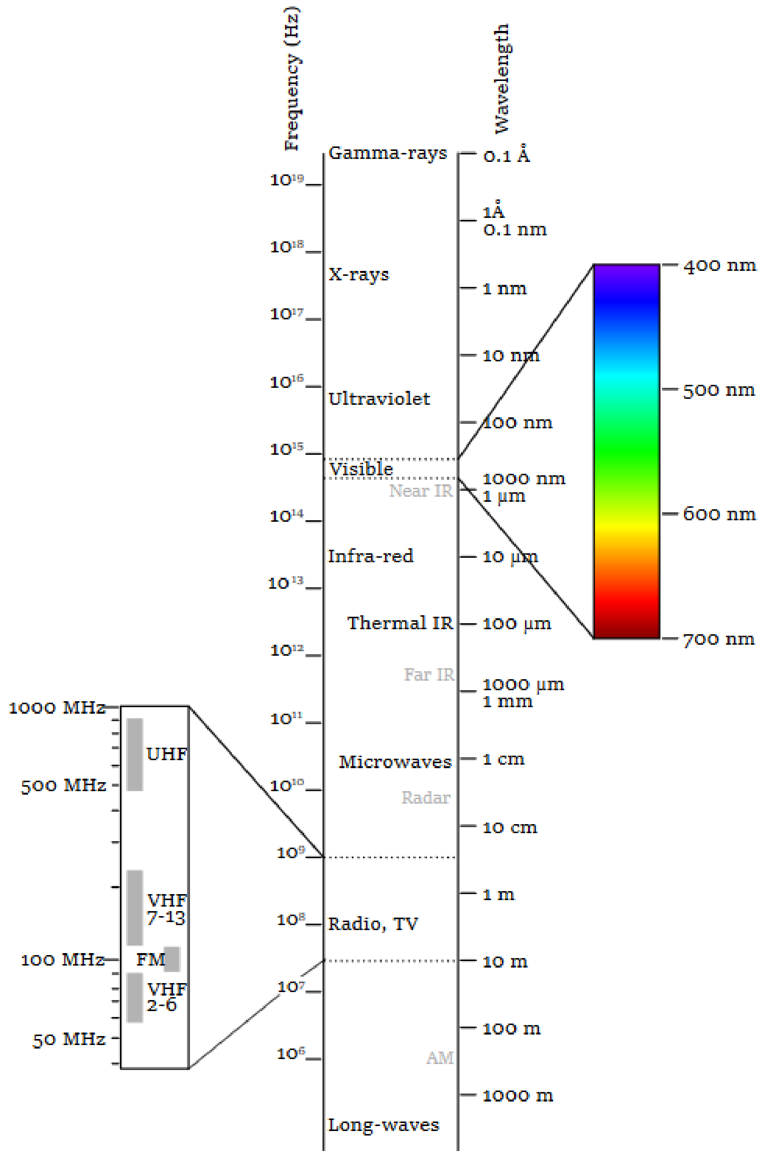
Boltzmann's constant relates energy and temperature k = 1.3806504 × 10^{-23} J/K

Electro magnetic spectrum

Top of atmosphere irradiance (Iqbal, 1983) $W/m^2/\mu m^1$
Dotted line: from Plank Law assuming Sun temperature 5785ºK
Continuous line: observed irradiance from satellites and rockets

Electromagnetic spectrum

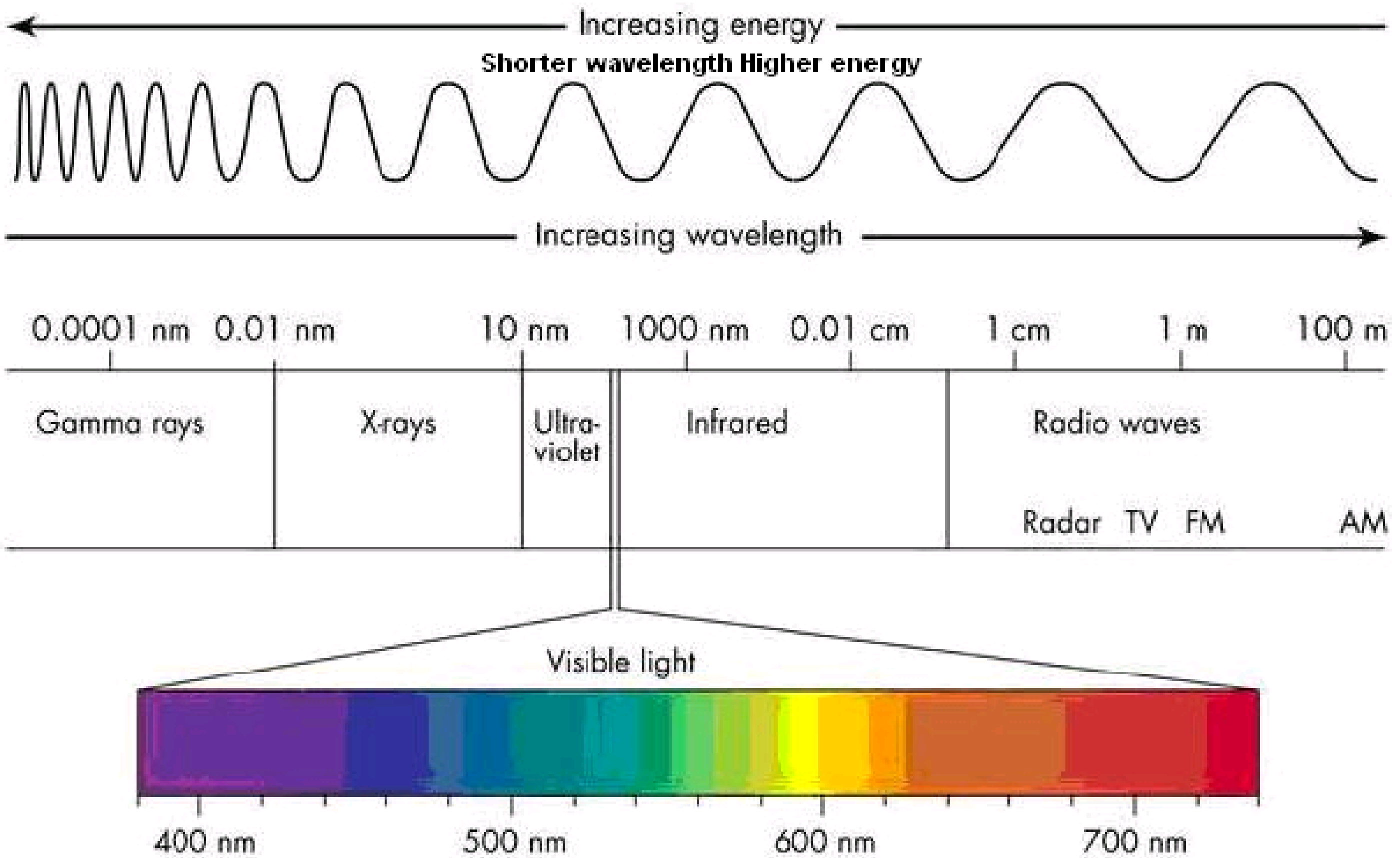
- Ionizing radiation:
  - Gamma rays
  - Ultraviolet: short wave
- Visible: sensible to human eye. Three main areas: blue, green and red. (0.4 – 0.78 μm)
- Infrared:
  - NIR Near infrared 1 μm
  - MIR Medium Infrared 10 μm
- Micro-waves and radio waves



Electromagnetic spectrum

Short wave longitude
High frequency

Long wave longitude
Low frequency

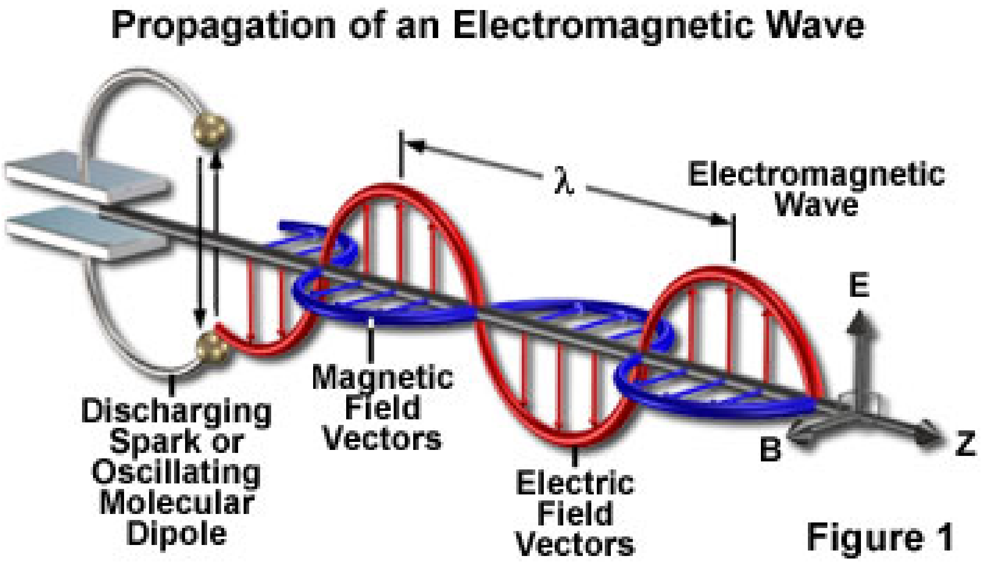


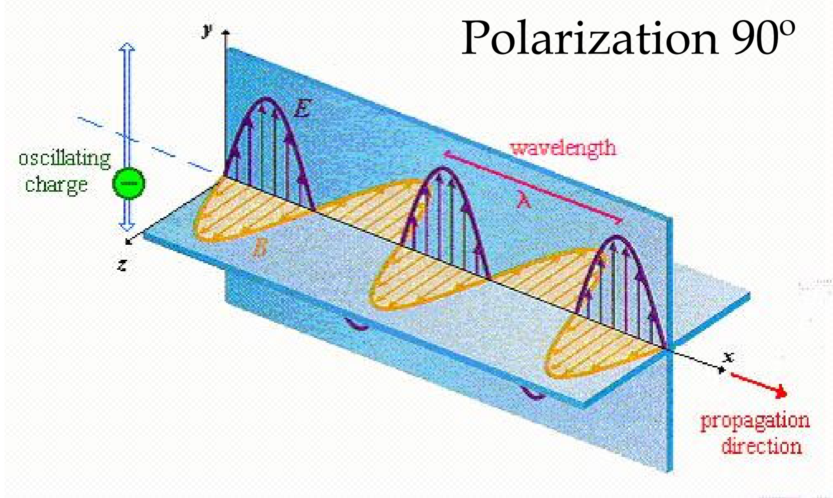
Gamma Rays
X Rays
Ultraviolet

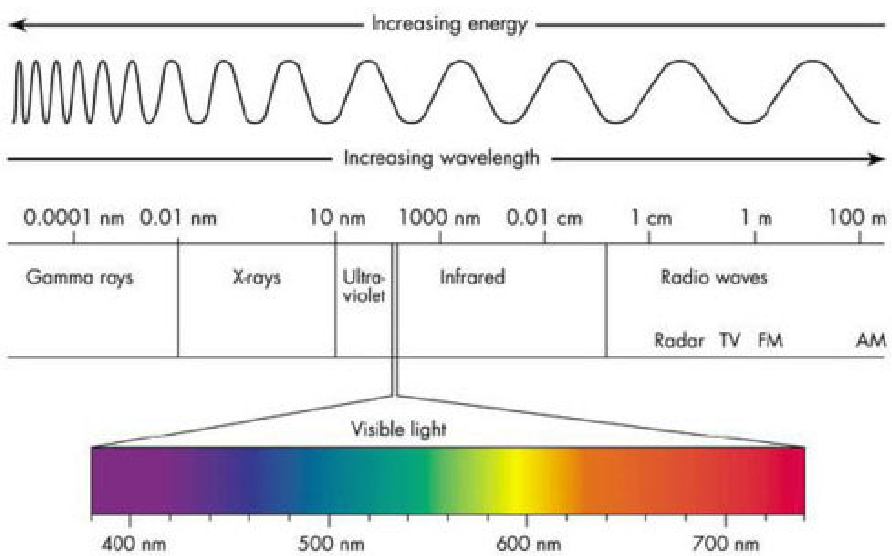
Visible 0.4-0.7 µm

- Infrared (Near NIR, medium MIR, thermal IR)
- Mycro-waves (radar, radio, T.V.)

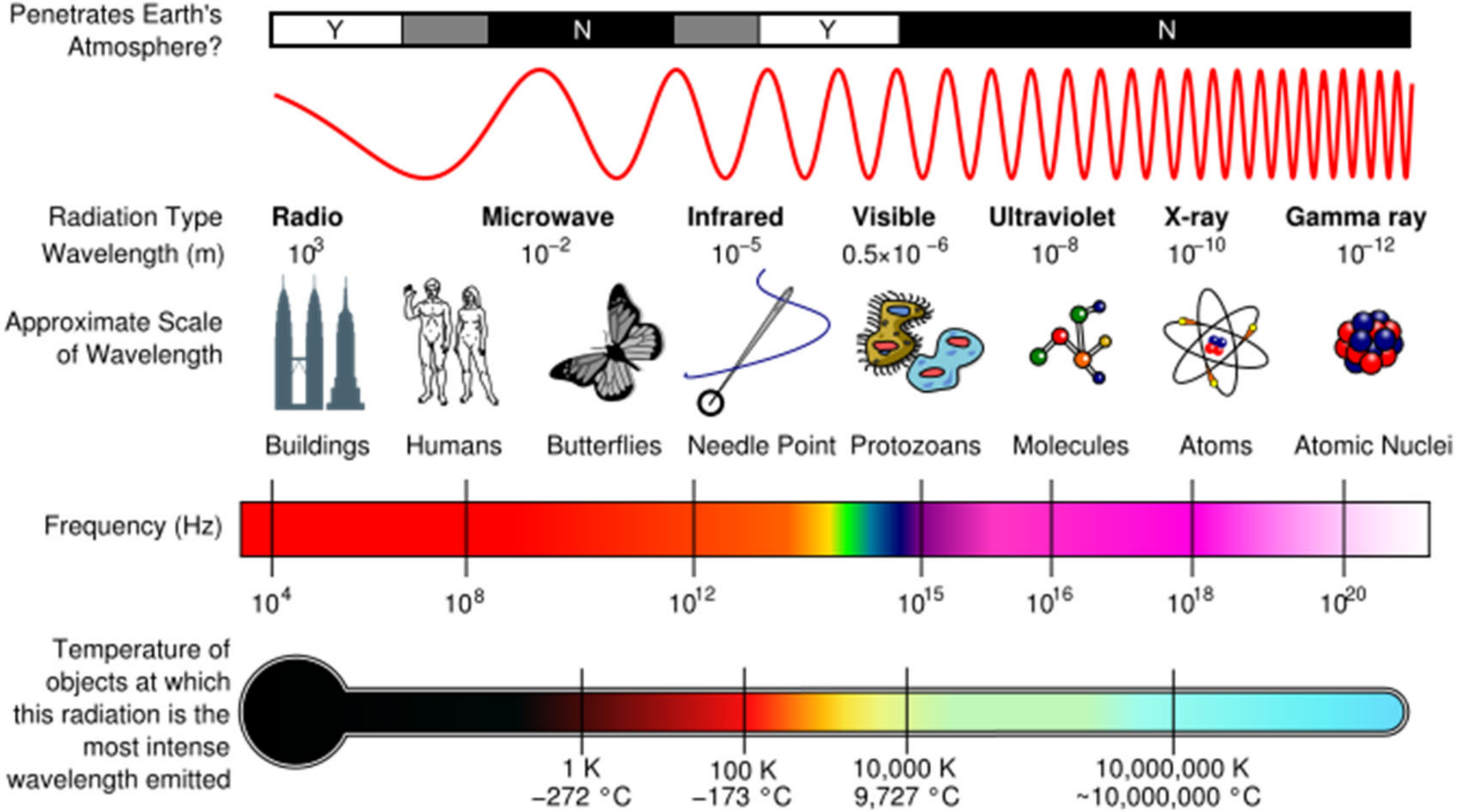
Electromagnetic waves







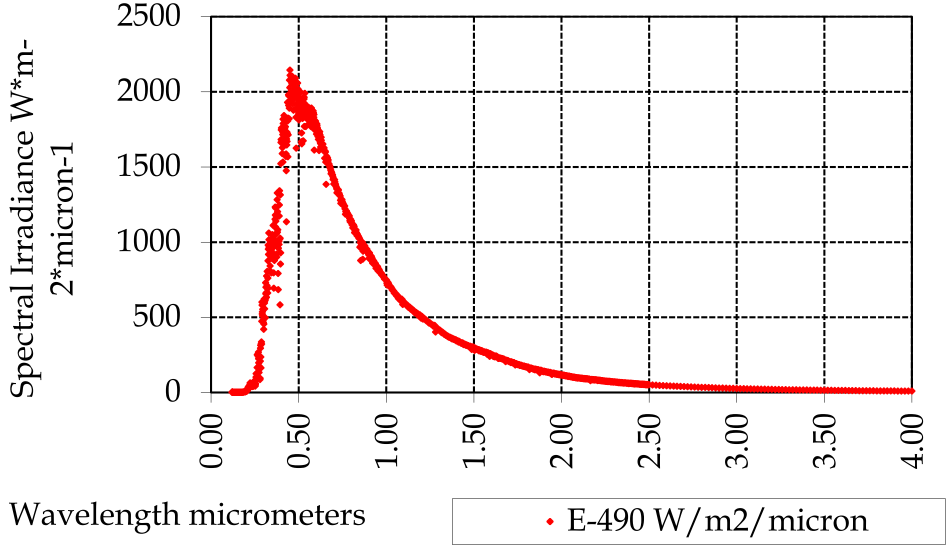
Electromagnetic waves properties



Solar energy and wavelength

Energy in the top of atmosphere TOA

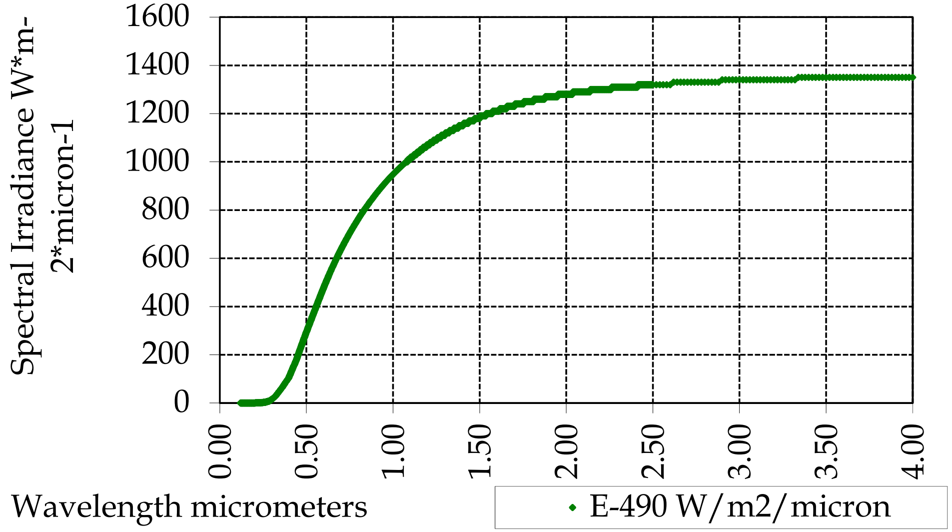
TOA: a given altitude where air becomes so thin that atmospheric pressure or mass becomes negligible



Solar energy in the top of atmosphere 1.366 – 1.367 Wm^{-2}

Solar constant

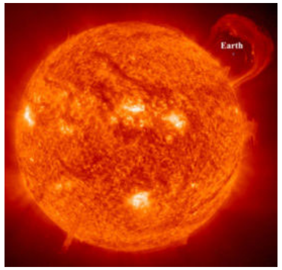
Integrating for all the wavelengths

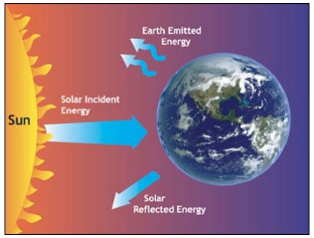


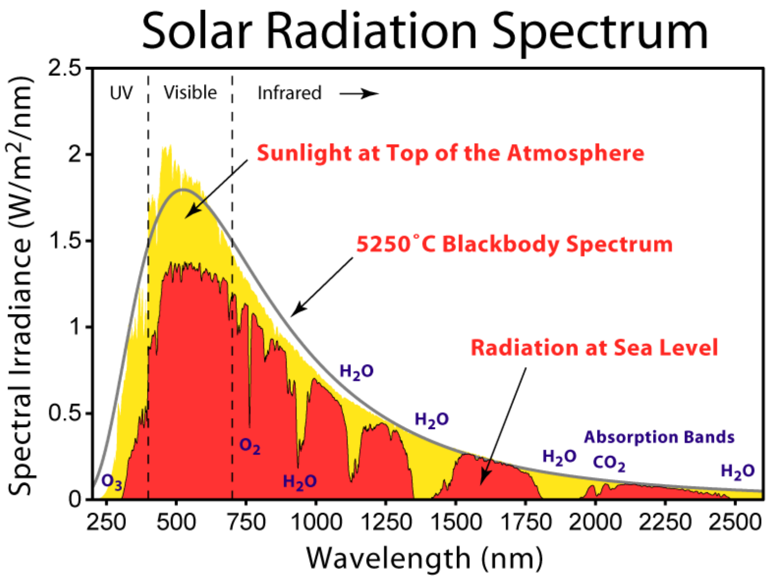
Energy from the Sun

Irradiance in the TOA (Top of Atmosphere): 1.367 W/m^2

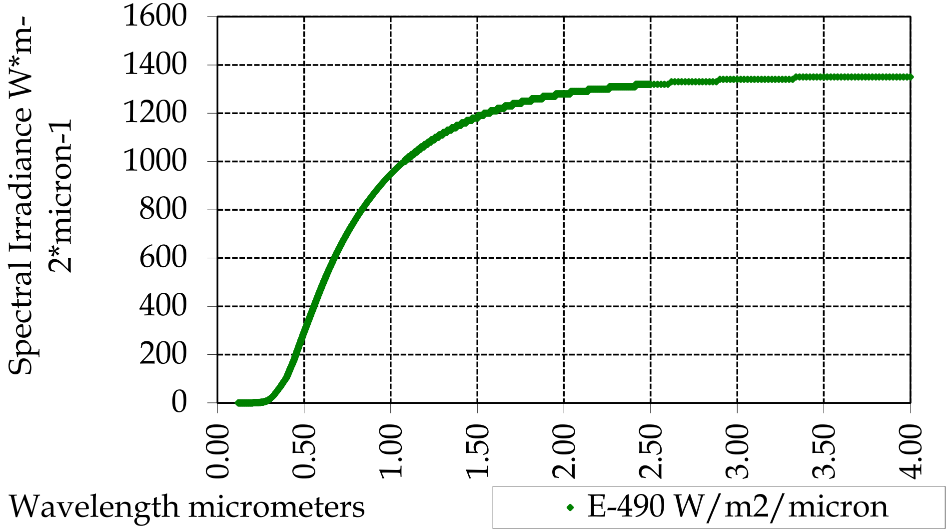
Irradiance at sea level with clear sky 1.000 W/m^2



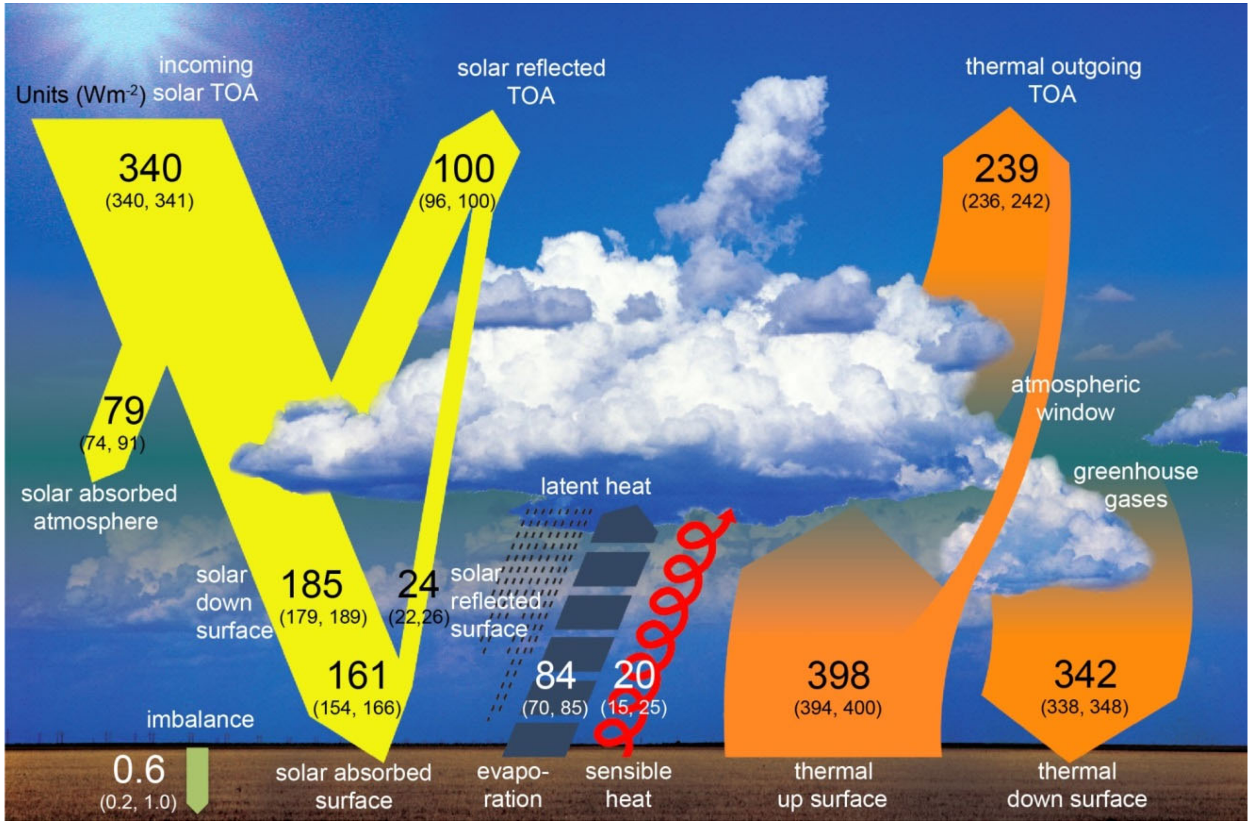




Integrated irradiance from Sun



Atmosphere interaction



Atmosphere interaction

Reflectivity: 35% of incoming solar radiation is reflected back to space).

- Clouds; Twenty-four percent of incoming solar radiation is reflected by clouds, 4% by the Earth's surface
- Scattering; Seven percent of incoming solar radiation is scattered back to space. Particles in the atmosphere can scatter incoming solar radiation

Absorption: about 17% of incoming solar radiation is absorbed at various levels in the atmosphere. Absorption is the process by which radiant energy is transferred to matter

- Gases, therefore, are not like black bodies that absorb equally and completely at all wavelengths. Rather, they absorb only at specific, often narrow ranges of wavelengths. Diatomic molecules such as nitrogen and oxygen (most of our atmosphere) can absorb energy by increasing the vibration of the bond between the two atoms. If the energy absorbed is great enough it may break the bond resulting in two free wheeling oxygen or nitrogen atoms traveling at high speeds.

http://eesc.columbia.edu/courses/ees/climate/lectures/radiation_hays/

Ozone absorption

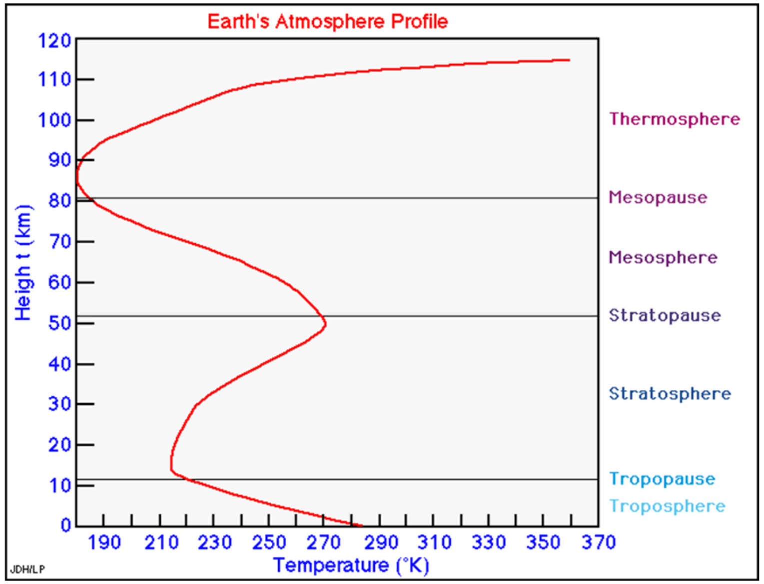
- In the highest regions of the atmosphere 110-100 km Oxygen molecules are therefore broken into oxygen atoms => O_2 + ultraviolet light = O + O
- For some distance above and below 80 kilometers there is little absorption of solar energy and consequently little heating of the atmosphere so the temperature reaches a minimum.
- Descending below eighty kilometers the atmosphere is heated by another process. The atmosphere gets denser (thicker) and with decreasing altitude form an ozone molecule => O + O_2 = O_3
- Ozone can in turn be broken up by ultraviolet light, 50-10 km, resulting in this reaction => O_3 + ultraviolet light = O_2 + O

Both:

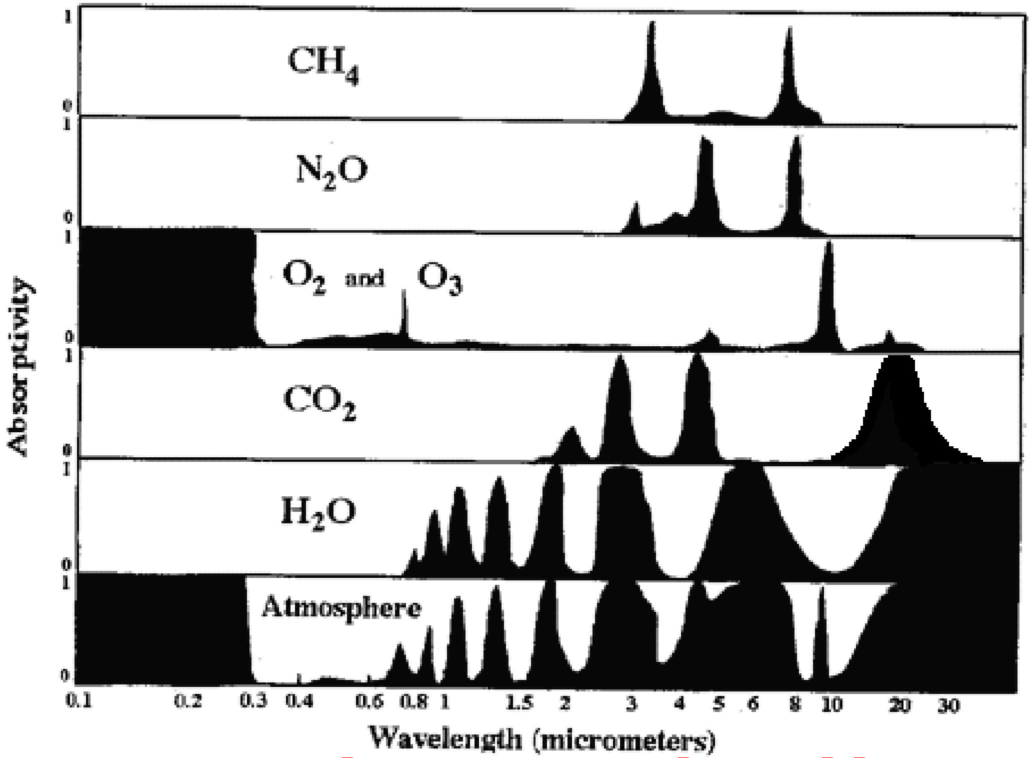
- the breaking up of oxygen molecules above fifty kilometers
- and ozone molecules at fifty kilometers and below.

Causes heating of the atmosphere that peaks at about 50 kilometers (the stratopause).

Between 50 and 10-15 kilometers (the stratosphere) the solar energy energetic enough to break up ozone (ultraviolet radiation) is used up and the atmosphere cools.



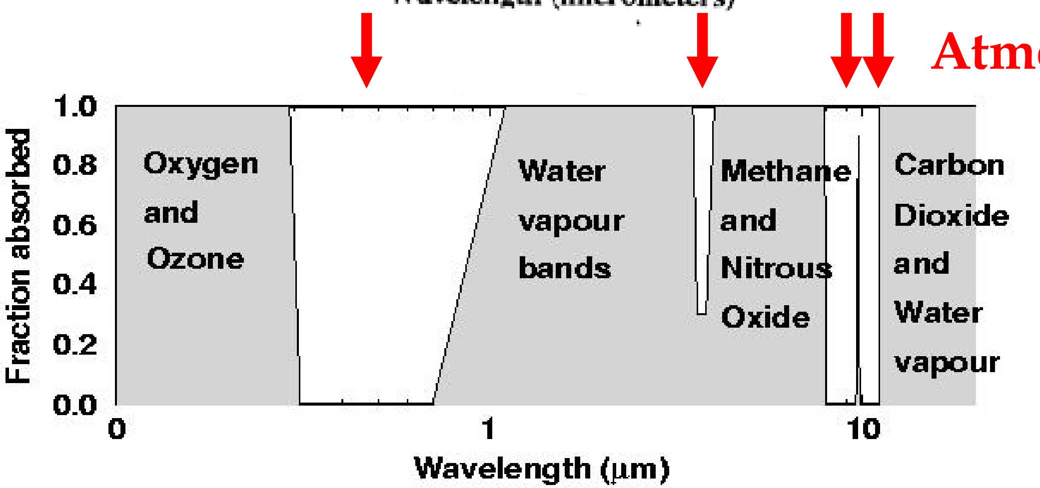
Energy absorption by chemical components



Absorption by chemical components, cero value indicates no absorption:

- Ultraviolet absorbed by Oxygen O_2 y Ozone O_3
- Infrared radiation: absorbed by Carbon Dioxide CO_2 and Water vapour H_2O

Atmospheric windows

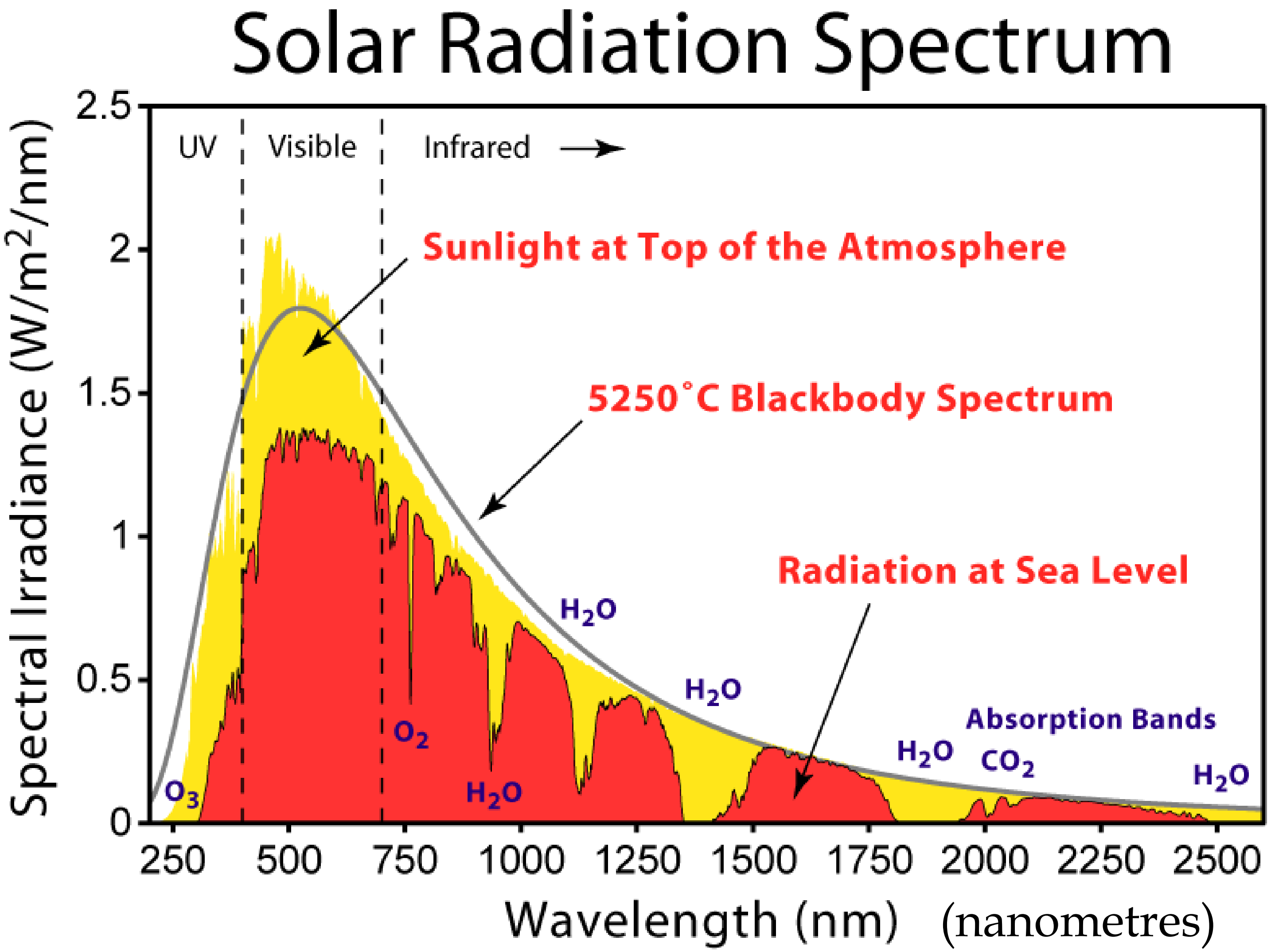


Atmospheric absorption of radiation

Simplified scheme

Waves > 15 µm blocked by CO2 y water vapour (clouds)

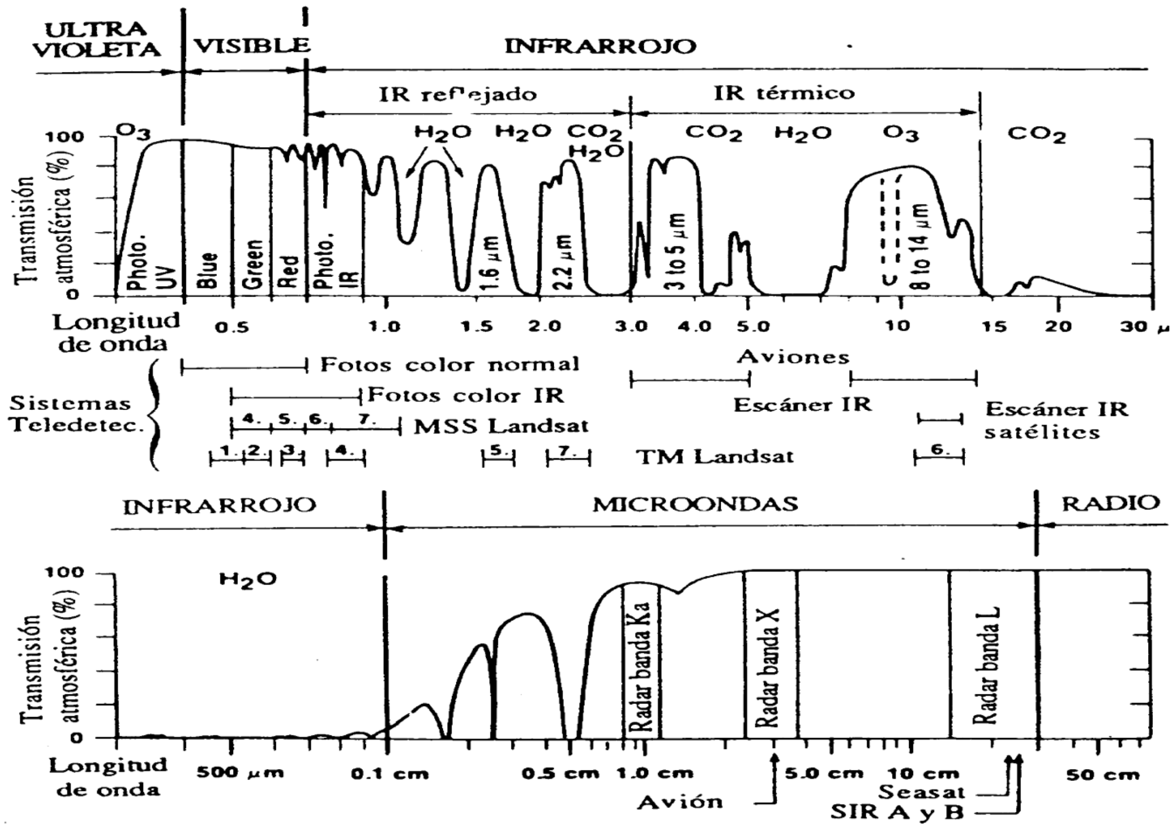
Solar Radiation Spectrum at TOA and Sea Level



(nanometres)

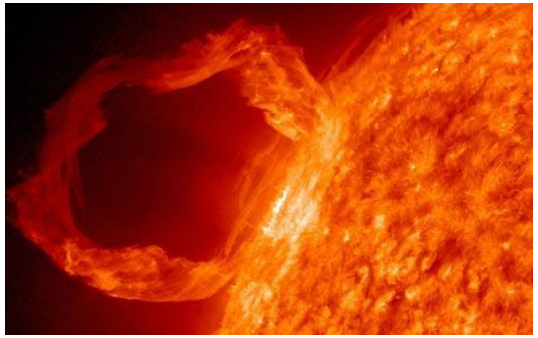
Chemical substances that absorbed energy

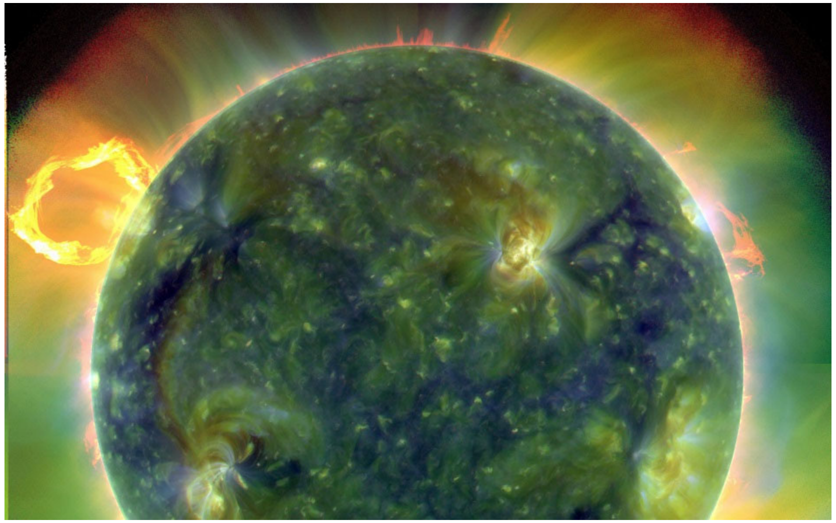
Energy Transmittance in the atmosphere and atmospheric windows

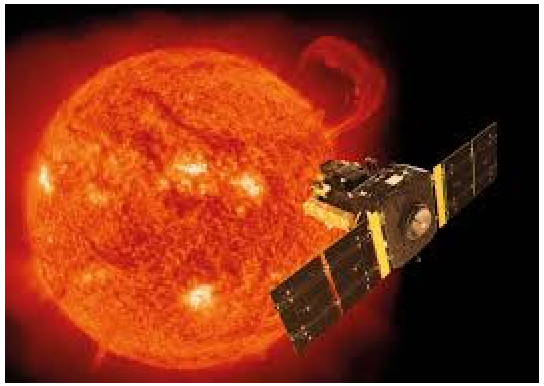


UV y Visible	0,30 - 0,75 µm
IR cercano	0,77 - 0,91 µm
	1,55 - 1,75 µm
	2,05 - 2,4 µm
IR térmico	8,0 - 9,2 µm
	10,2 - 12,4 µm
Microondas	7,5 - 11,5 mm
	> 20 mm

Solar variation

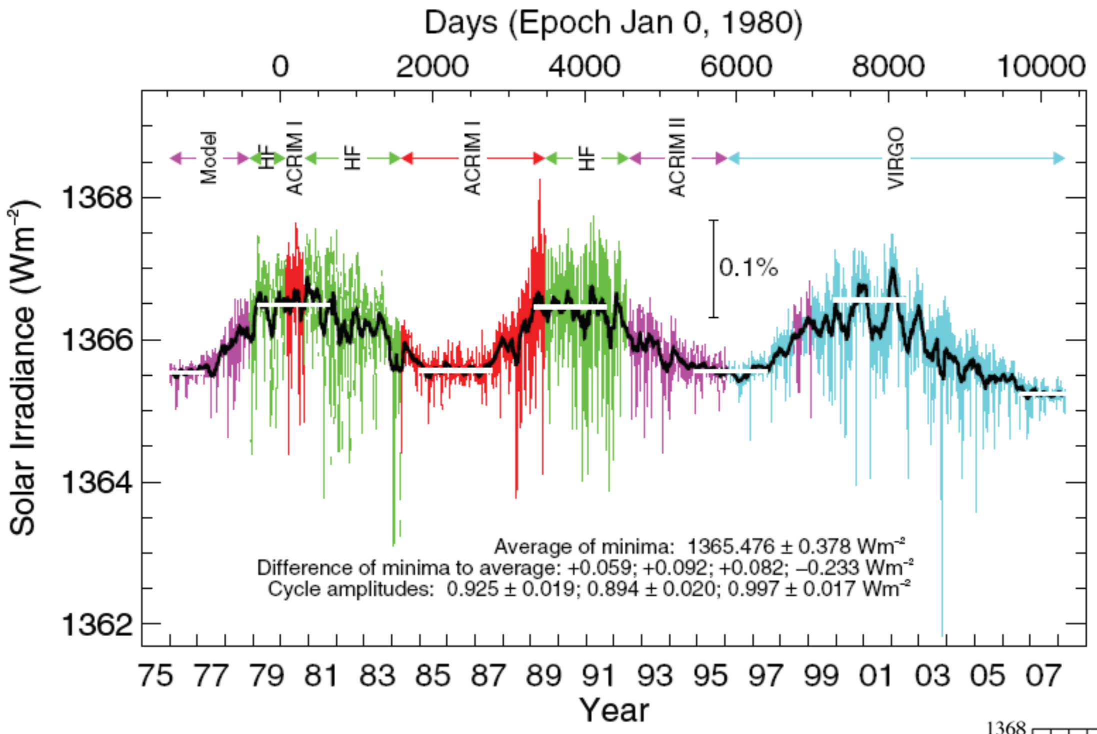




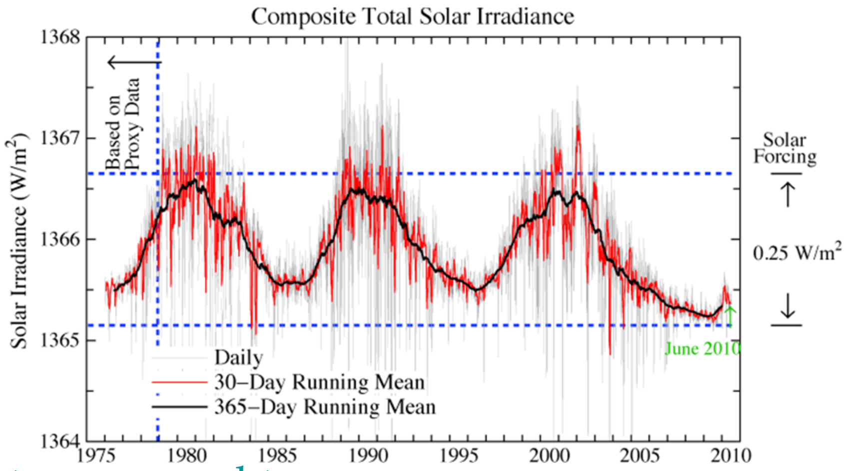


Satellite SOHO.
ESA–NASA Solar and Heliosphere Observatory
Launched 2-Dic-1995

Solar Irradiance at the top of atmosphere



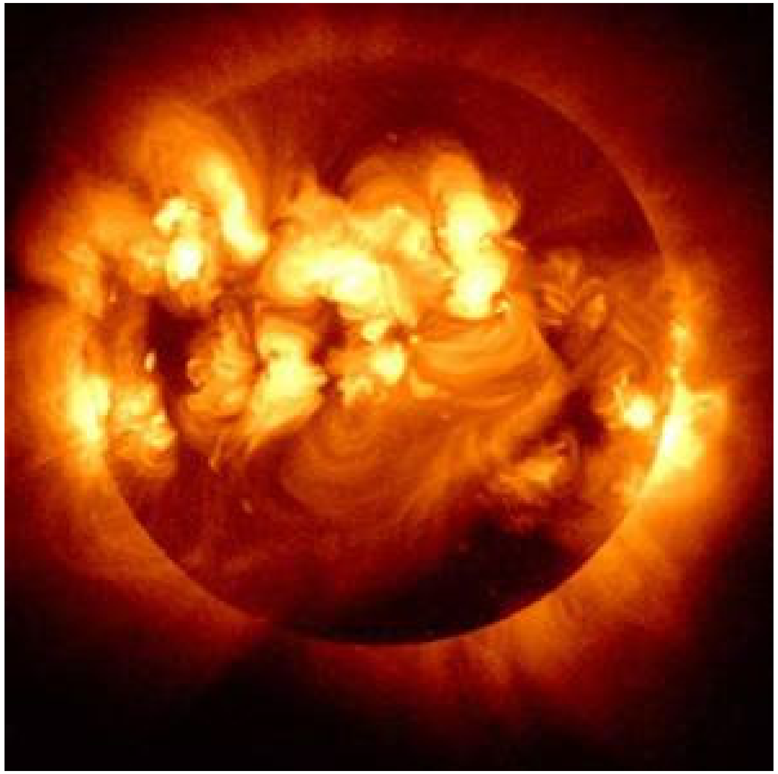
Total Solar Irradiance, TSI

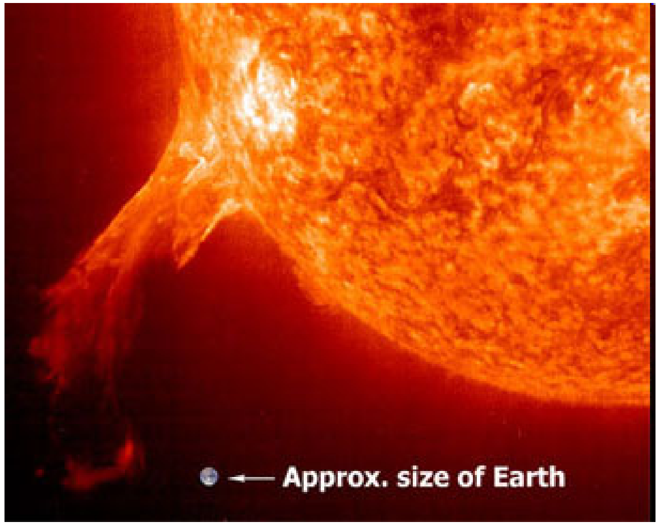


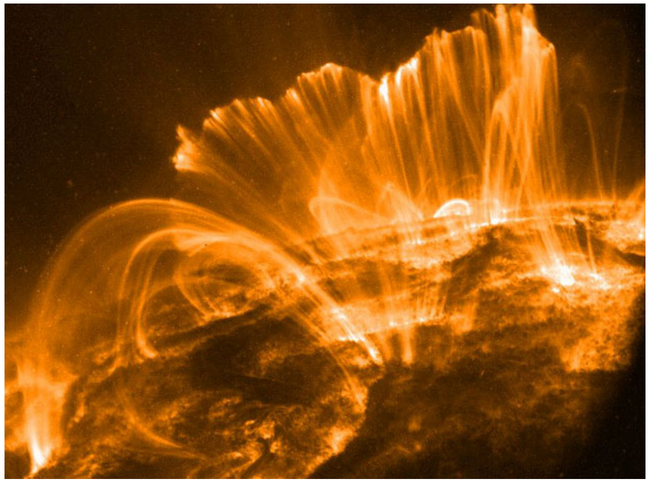
http://www.ngdc.noaa.gov
http://lasp.colorado.edu/sorce/data/data_product_summary.htm

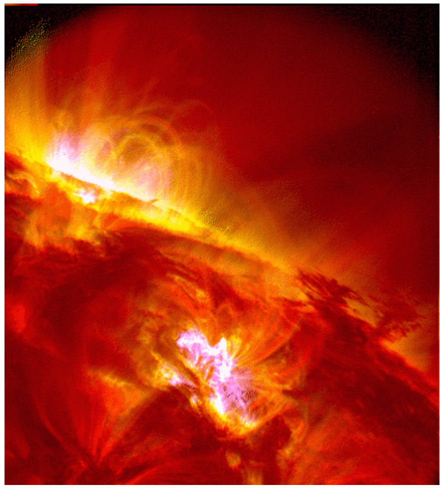
Variation in the Solar activity. Solar cycles

The Solar activity has variations and the Solar Irradiance that reach the Earth also has these variations









Sunspots are temporary phenomena on the Sun's photosphere that appear as spots darker than the surrounding areas

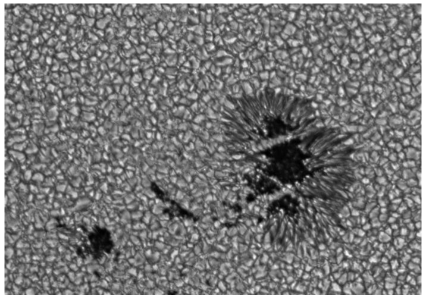
“Sunspots” historical records

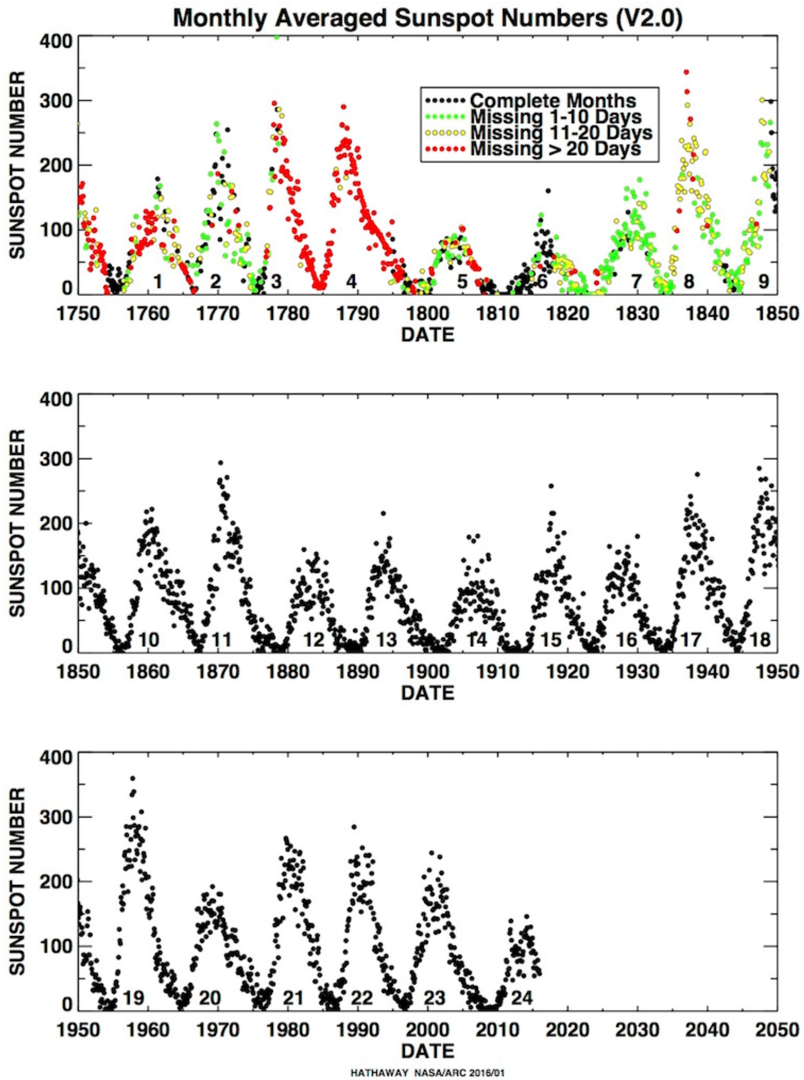
“Sunspot number" computed daily

the sunspot number (Rudolph Wolf in 1848):
R = (10*G + S)*K
G = the number of sunspot groups observed
S = the count of all sunspots in all groups
K = a scaling number to compensate for variables
To combine different observers

11 years cycles

Wolf number (1864)
(International Sunspot
Number or Zurich number)



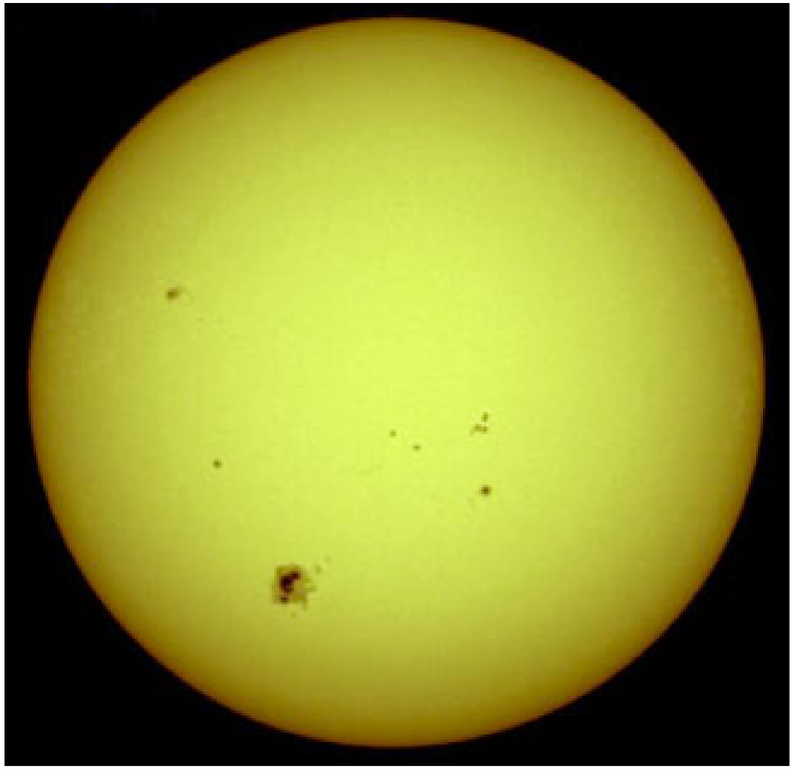


Actually (from 1990), only groups are counted.
Two International Sunspot Number "official“:

- by Sunspot Index Data Centre in Belgium.
- NOAA by US National Oceanic and Atmospheric Administration.

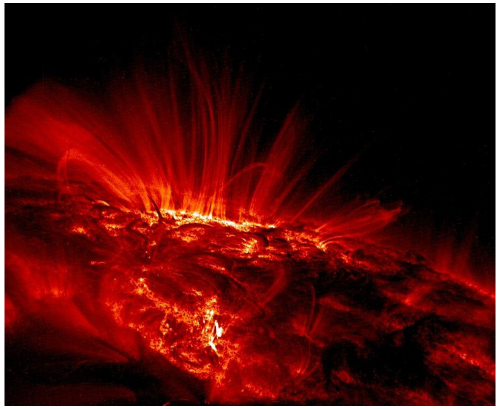
https://www.astroleague.org/content/what%E2%80%99s-sunspot-number

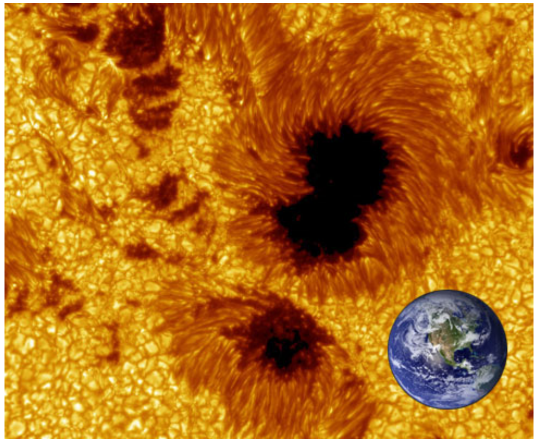
Sunspots and Solar Radiation



Temperature in the photosphere 5700 K
Temperature in the centrum of the darkness areas (Sunspots) 3700 K

Sunspots may last a few days, and larger ones may last a few weeks.



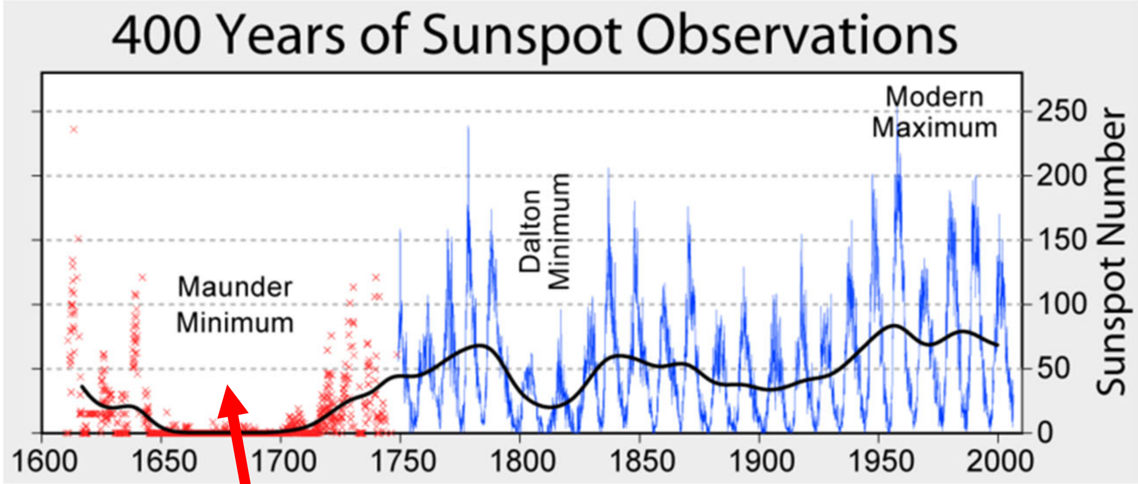


Granules are relatively small (around 1000 km)

Relative size of the Earth with a sunspot

Sunspots and climate.
Maunder minimum 1650-1700

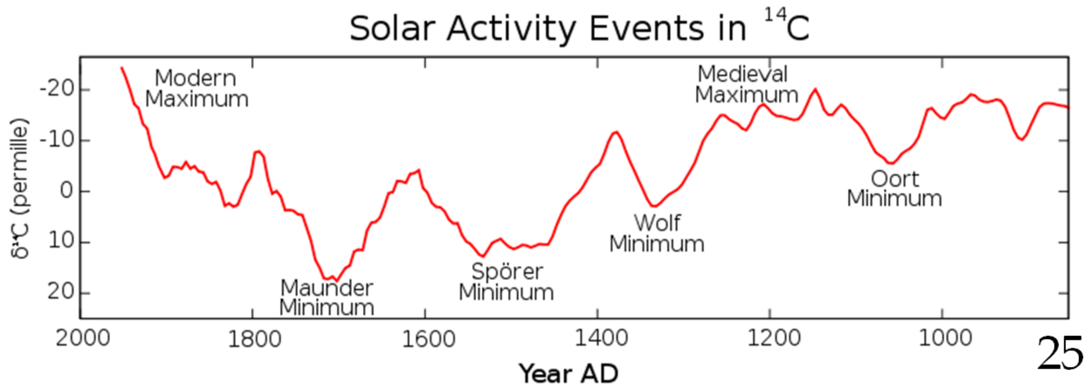
Maunder minimum. Low Solar activity between 1645 y 1715, "Little Ice Age"



Evidence of the relationship between solar activity and climate on earth.
Minimum of Dalton (1790-1820) year without summer 1816 (ash from Tambora volcano).

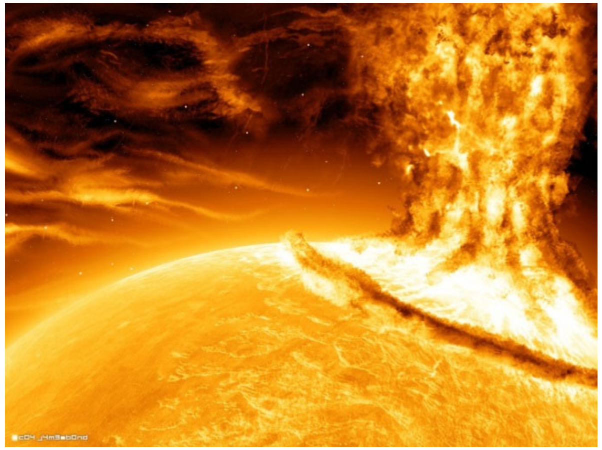
Támesis river frozen 1677

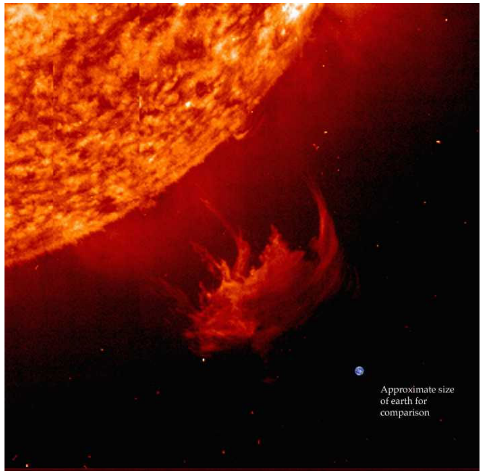
Reconstruction of the existence of other previous solar minima from carbon 14 in the rings of trees.
Minimum of Spörer (1450-1540)

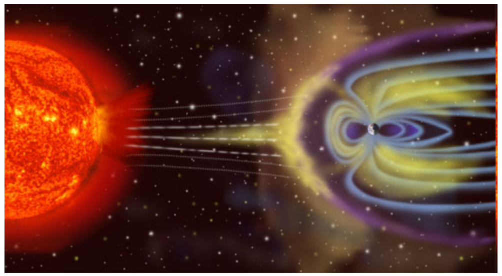


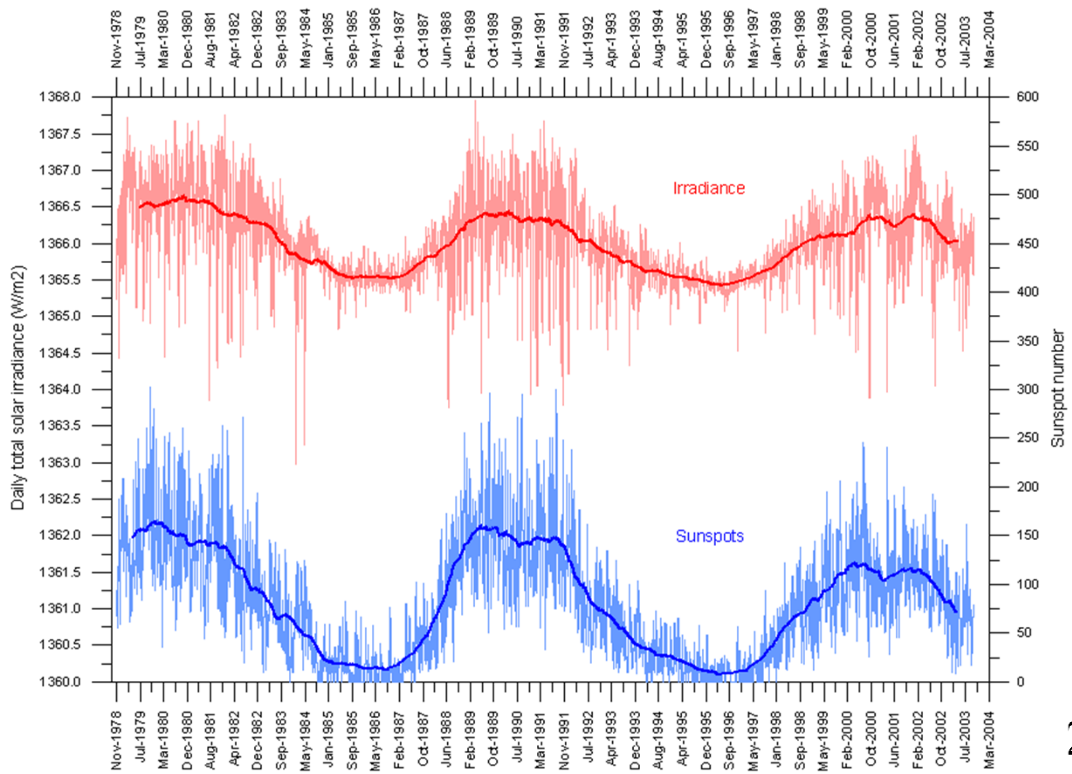
Sunspots and Solar explosions

- The greater number of sunspots increases the energy that reaches the earth. Sunspot is due to a solar explosion, around the sunspot is brighter and emits more energy
- The sunspot is a relatively cold zone but due to a large heat output (flare)
- Solar explosion or solar storm occur around sunspots







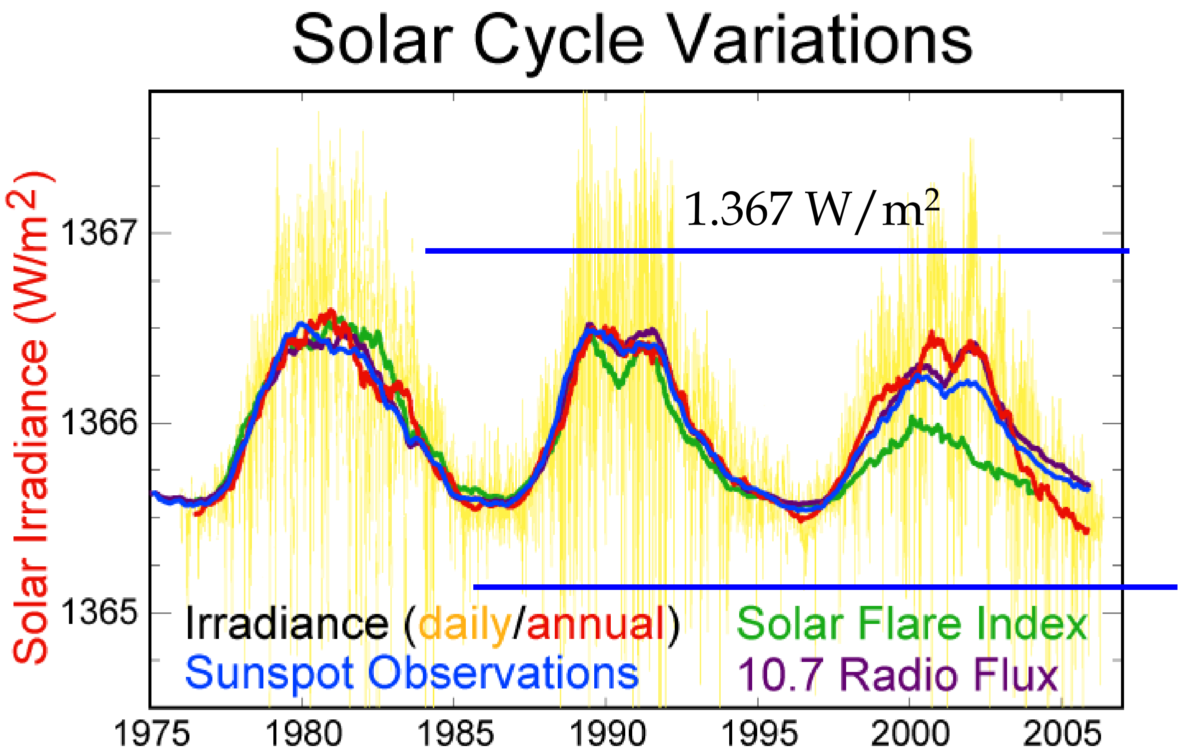


Solar Energy reaches the top of atmosphere

Solar constant at one AU, reach the Earth
(Commission for Instrumentation and Observation Methods, October de 1981)
Oscillation between 1.365 y 1.367 Wm^{-2}. Consensus 1367 ± 4 Wm^{-2}

$$I_{SC} = 1367 Wm^{-2} = 4.921 MJm^{-2}h^{-1}$$

Now is 1361 W/m2

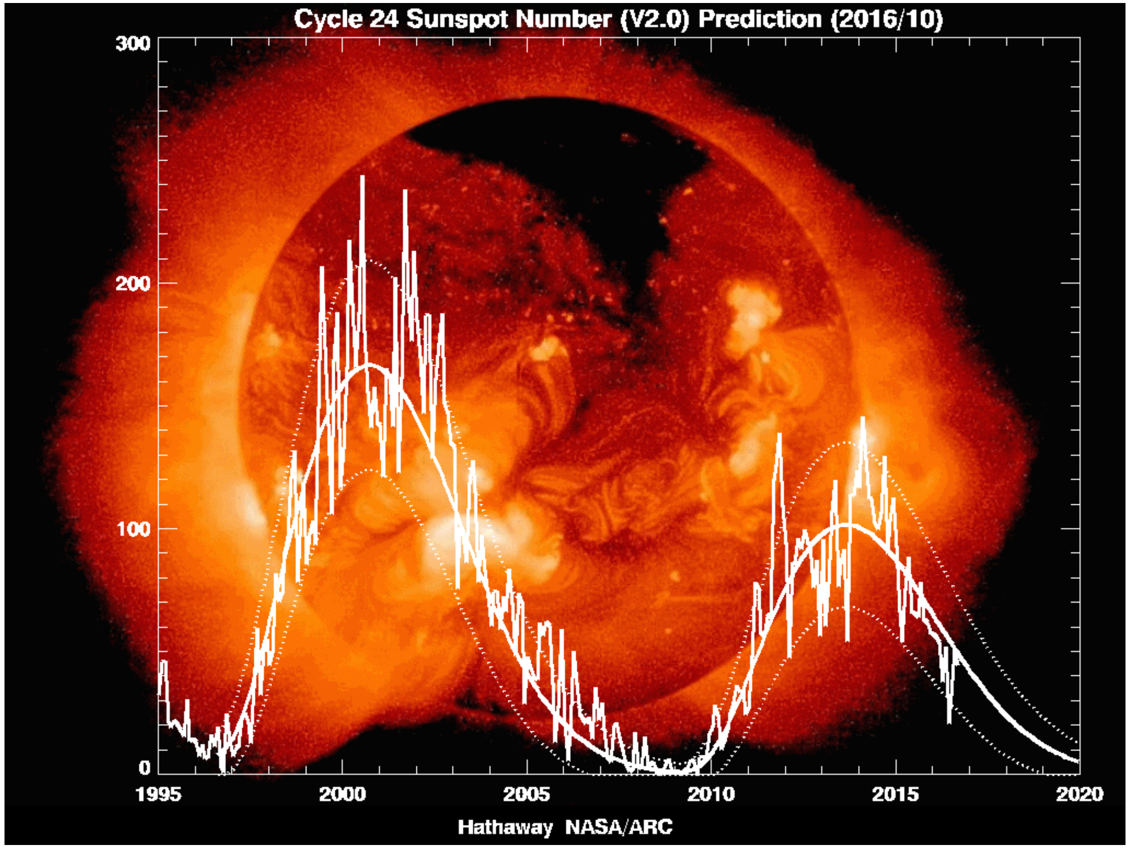


1.365 W/m²

Energy variation at top of atmosphere 2 W/m²
Mean around the entire surface of Earth
(1/4) => **0.5 W/m²**

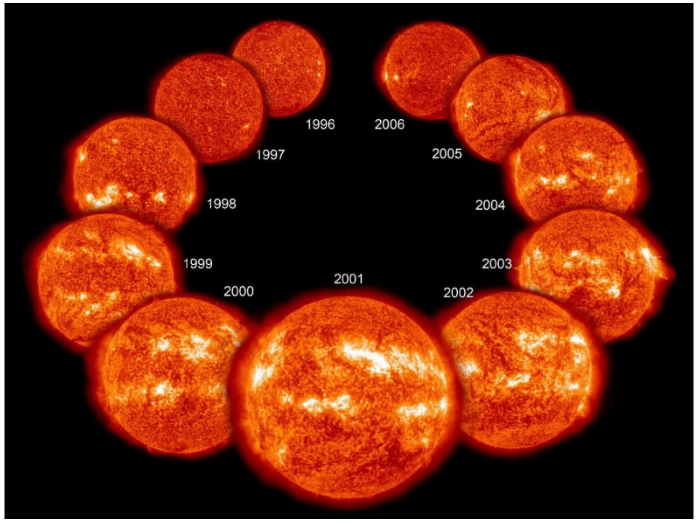
Greenhouse gases GHG
- Actual **1.5 W/m²**
- 2100: **4-8 W/m²**

Future evolution of Sunspots

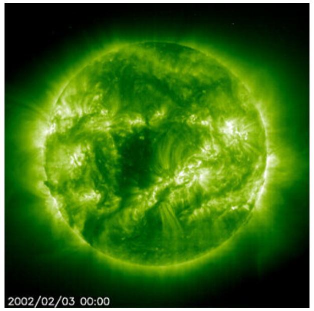


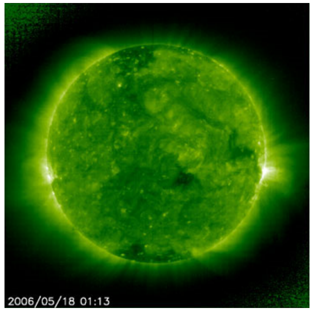
Cycle nº 24

Rayos-x Solar Radiation, active phase (1991, left) until inactive phase (1995, right)
Satellite images from Yohkoh each 4 months.
Satellite catastrophic failure 2001 (NASA, Yohkoh Science Project, YPOP)



Maximum
2000 a 2002





Minimum
2006 - 2010

http://solarscience.msfc.nasa.gov/
http://solarscience.msfc.nasa.gov/SunspotCycle.shtml

Solar constant

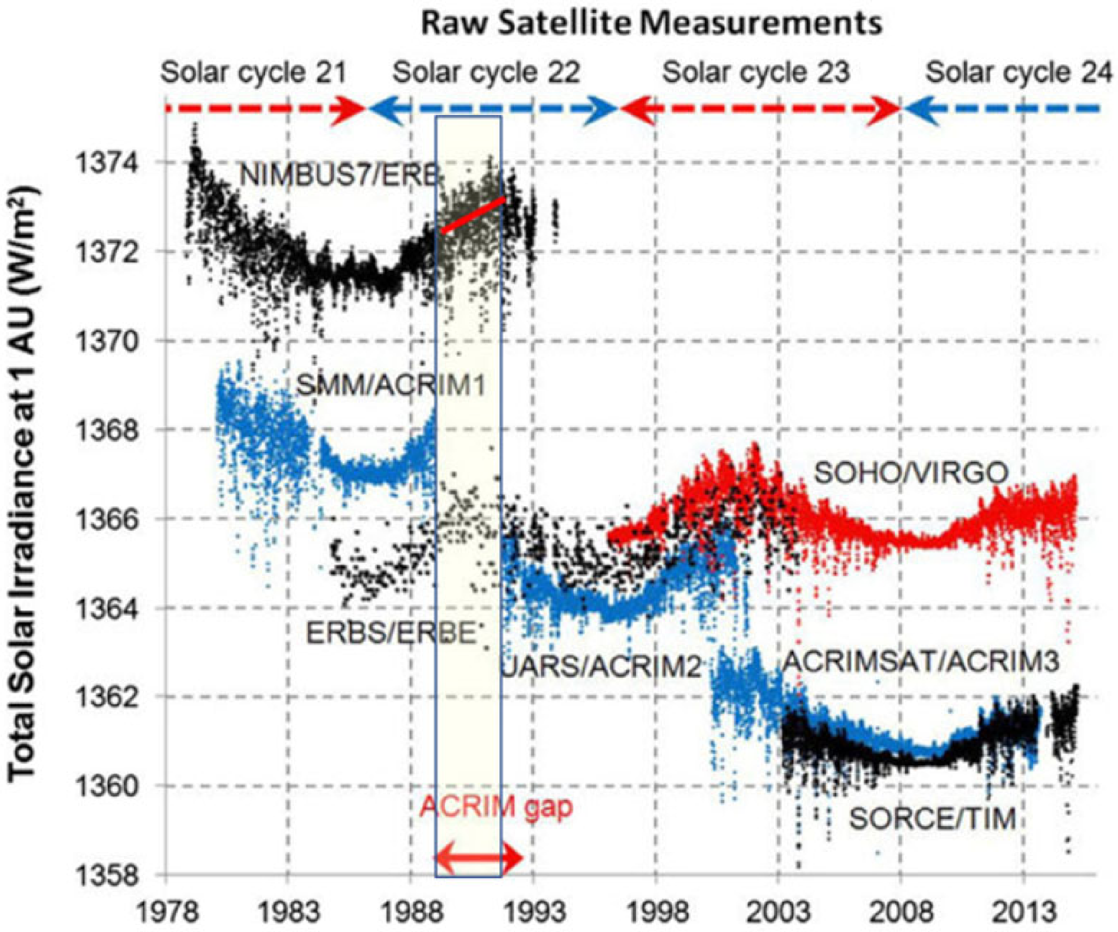
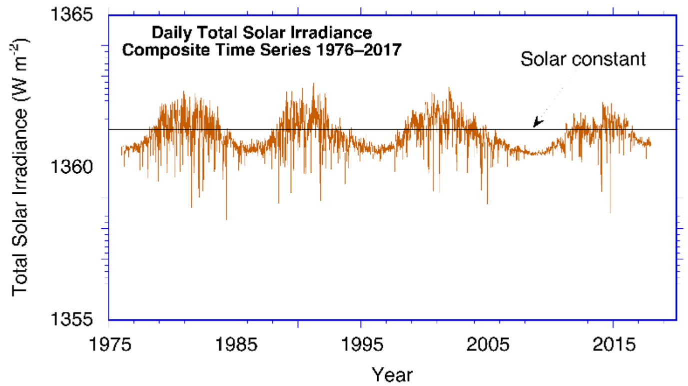


Figure 2. Raw satellite total solar irradiance (TSI) measurements. The ACRIM gap is identified in yellow. The trend of the NIMBUS7/ERB instrument in the ACRIM gap is emphasized with a red line. Source: (Soon, Connolly and Connolly 2015).

Now the solar constant is 1361 W/m^2



More precise measurements ACRIM (Active Cavity Radiometer Irradiance Monitor)

2. Potential Solar Energy

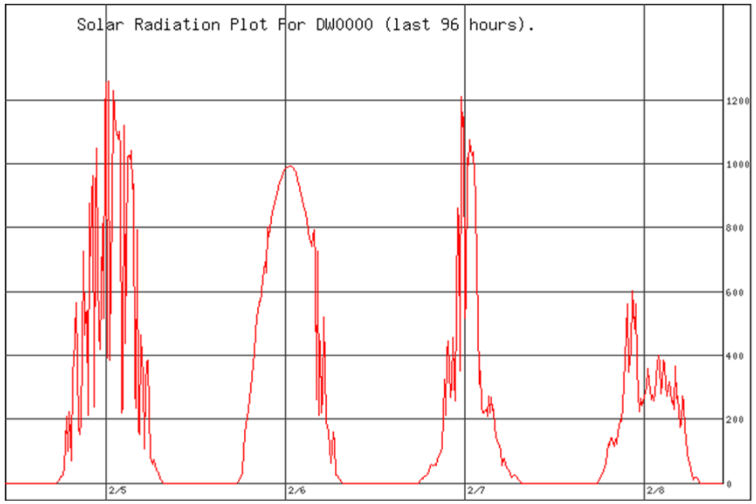
Energy from the Sun: Irradiance

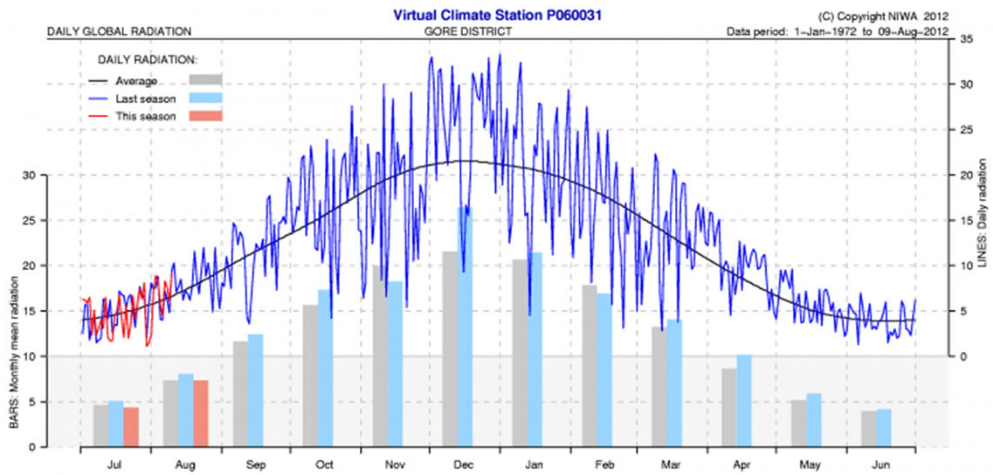
Irradiance (power) in a surface, depends on:

- Solar angle (day of the year, hour of the day)
- Weathers (cloudiness)
- Surface orientation

Irradiance data (hourly and daily)

- From direct observations (pyranometer)
- From theatrical estimations: latitude, cloudiness





http://pveducation.org/pvcdrom/introduction/solar-energy

Energy from the Sun: Irradiance

A **pyranometer**, used to measure global irradiance

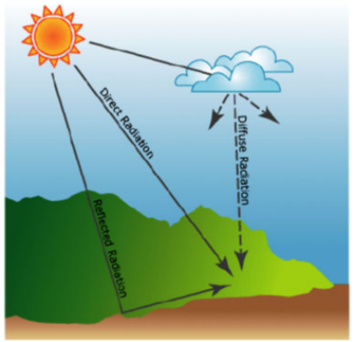
A **pyrheliometer**, mounted on a solar tracker, is used to measure Direct Normal Irradiance (or beam irradiance)

- Direct Normal Irradiance (DNI)

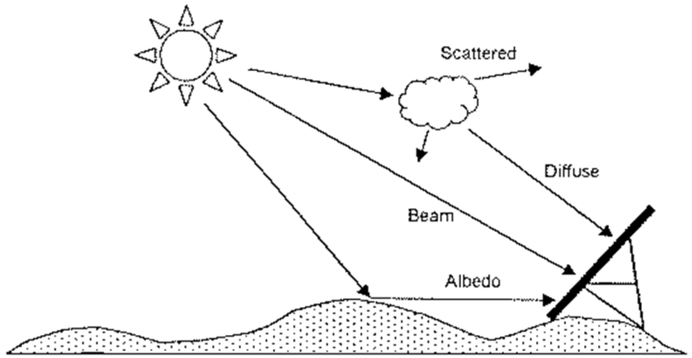
- Diffuse Horizontal Irradiance (DHI)

Source: nrel.gov

- Global Horizontal Irradiance (GHI)



Source: esri.com



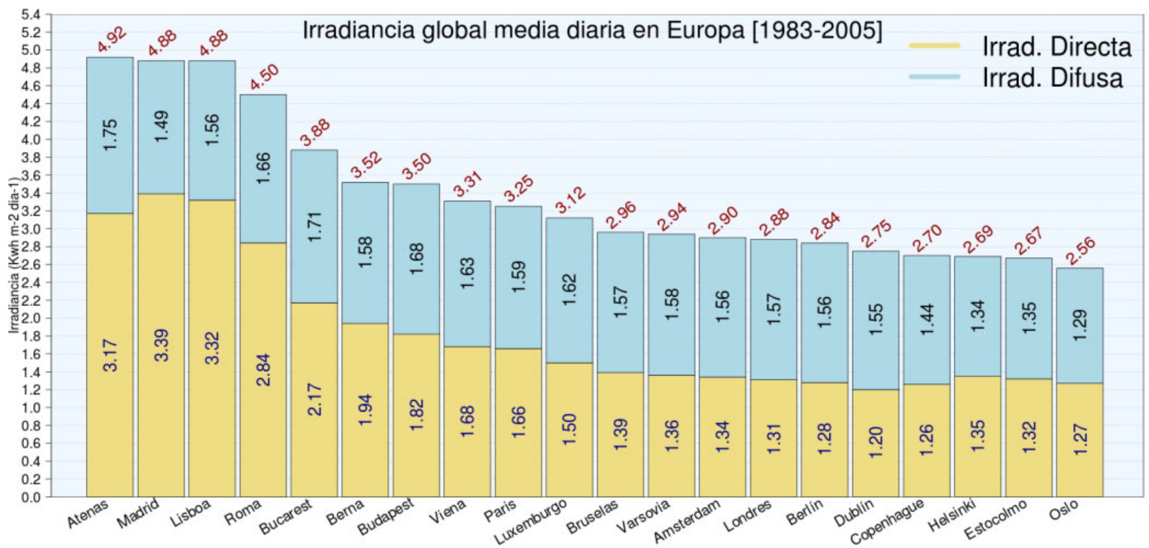
Daily Irradiation components kWh

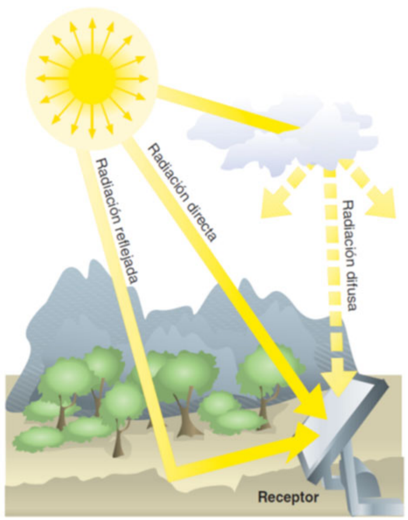
Irradiation (kWh): the sum of the total irradiance (kw) in a day
"Global daily Irradiation" Gd the sum of:

$$G_d = I_d + D_d$$

- Direct radiation Id:
- Diffuse Radiation Dd: disperseb by the atmosphere and clouds.
- Reflected Radiation "albedo": reflected by the land surface. (It is usually negligible or is integrated into the diffuse)

Irradiation in Europe:
The diffuse is similar
1.5 kWh/m²-día
Direct changes more
Spain 3.5 kWh/m²-día





Diffuse irradiation Estimation in a horizontal surface D_d (KWh/m² día)

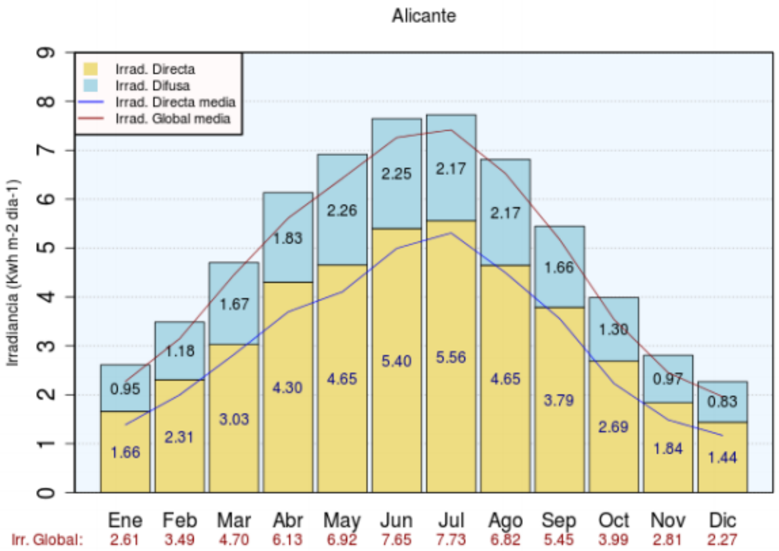
$$D_d = G_d\,[\,1.39 - 4.027K_d + 5.531\,K_d^2 - 3.108\,K_d^3]$$

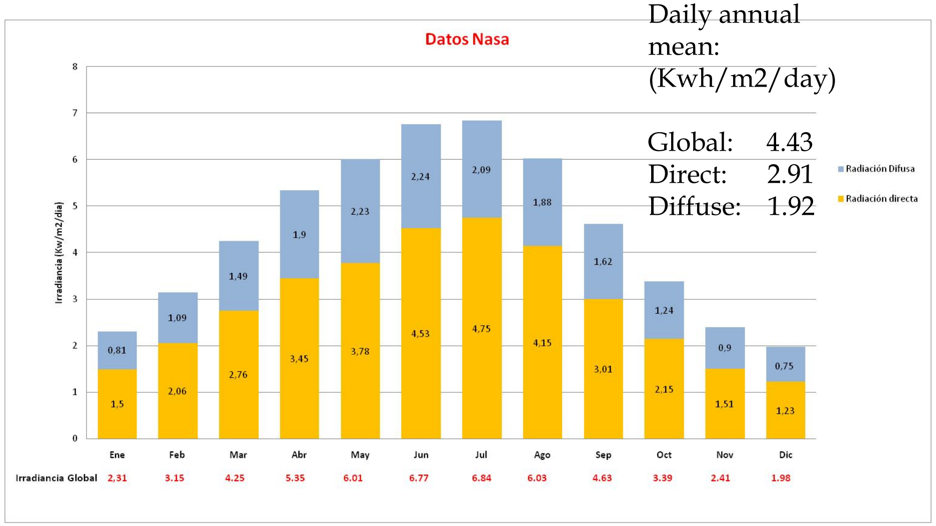
G_d = global irradiation observed in a horizontal surface
K_d = Atmospheric transparency index = G_d/G_{0d}
G_{0d} = Solar irradiation at the TOA in a horizontal surface

Diffuse and direct Irradiation (kWh)

Mean Irradiation in a normal day

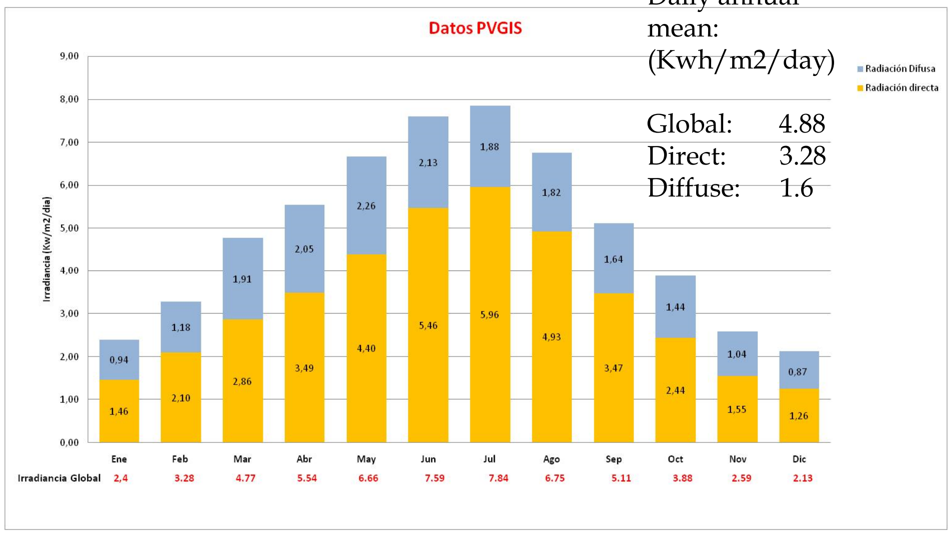
It is lower than the irradiation day clear, because it is considered a cloudy percentage of days





Daily annual mean: (Kwh/m2/day)

Global:	4.43
Direct:	2.91
Diffuse:	1.92



Daily annual mean: (Kwh/m2/day)

Global:	4.88
Direct:	3.28
Diffuse:	1.6

Example: Alicante data

Energy from the Sun

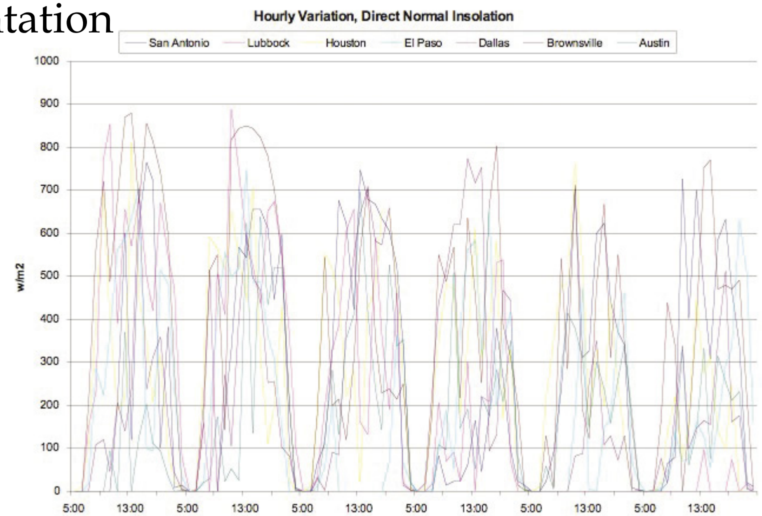
Potential Solar Energy: $3{,}9 \times 10^6$ EJ/year, global irradiance over the earth (land and seas). 100% surface occupied and 100% efficiency of the solar modules.

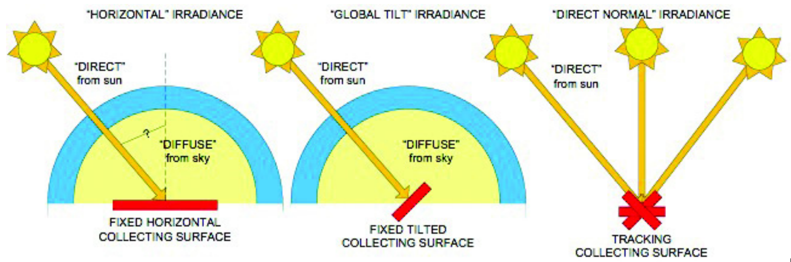
- Realistic values: only the land and real efficiencies: 1.575 - 49.837 EJ/year
- 3 to 100 times the global energy demand on the Earth. Earth´s demand in 2008, 500 EJ, in 2050 1.000 EJ.

Irradiation and electrical production depends on:
Latitude (hours of sun) – Cloudiness- Solar module orientation

W/m²	**Solar constant TOA**	**1,361**
W/m²	**Irradiance at sea level in a clear day**	**1,000**
kW/m²	Irradiance in the middle day	1
h/day	h/day equivalent: Valencia (variable during the day, latitude, cloudiness)	5.5
kWh/m²-día	Irradiation	5.5
días	Días/año	365
kWh/m²-año	Irradiation (annual)	2,008
	performance	0.75
kWh/m²-año	**Potential annual production**	**1,506**

Irradiance (Power) kW/m2

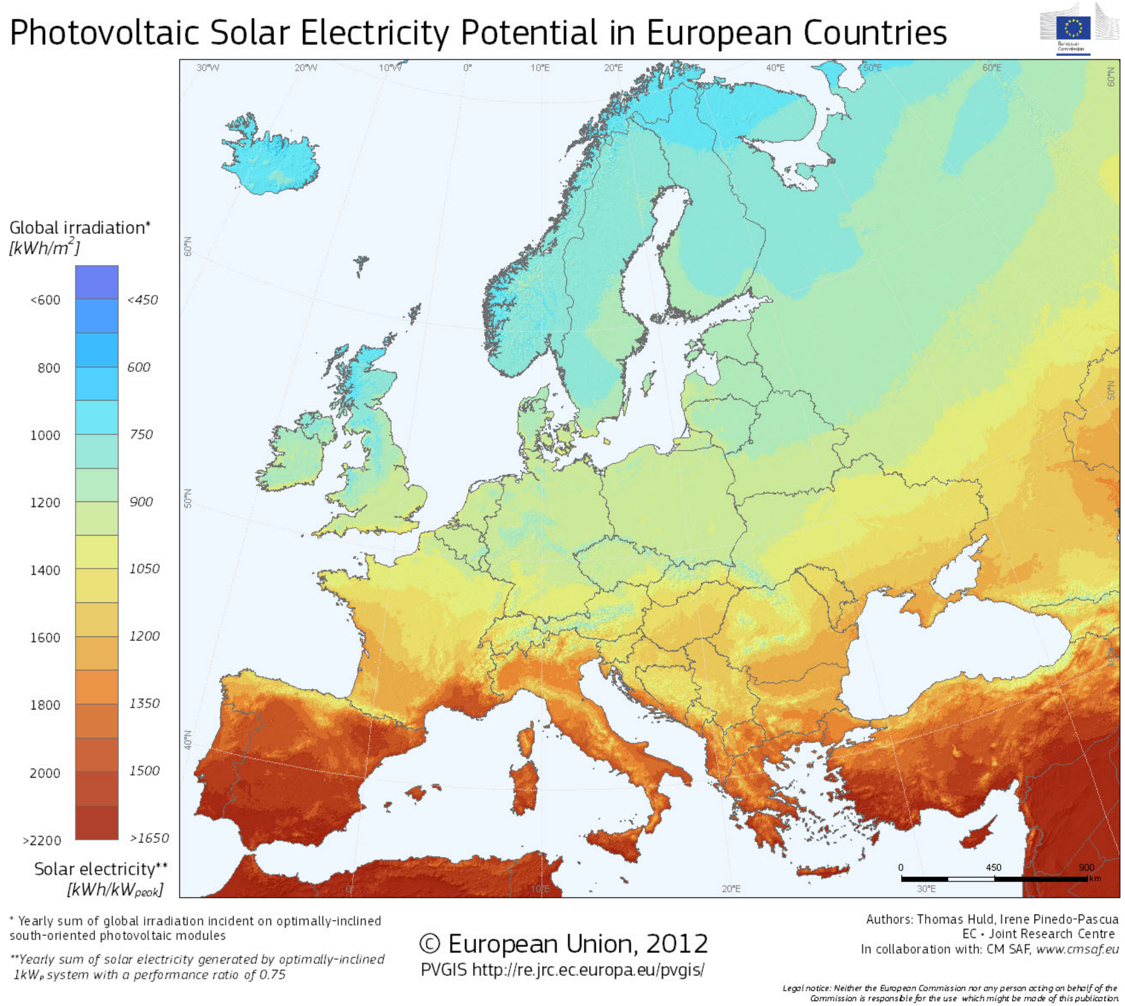




Fixed horizontal – Fixed tilted – Tracking

Annual photovoltaic potential in Europe kWh/m²-año
Irradiation

Irradiation (Insolation): Total energy in a day kWh/m2/day



Annual production depends on:

- distribution of sunshine hours during the year
- and the irradiance at those hours

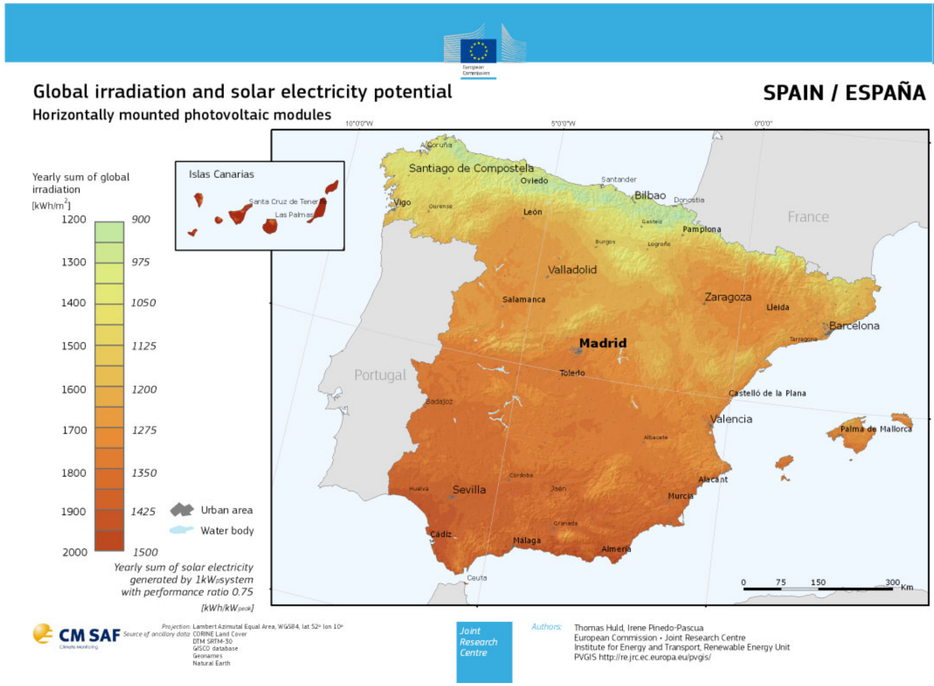
Spain:
(Fixed tilted)

kWh/m² - year	min	max
Irradiation	1,400	2,000
Electricity potential production (x 0.75)	1,050	1,500

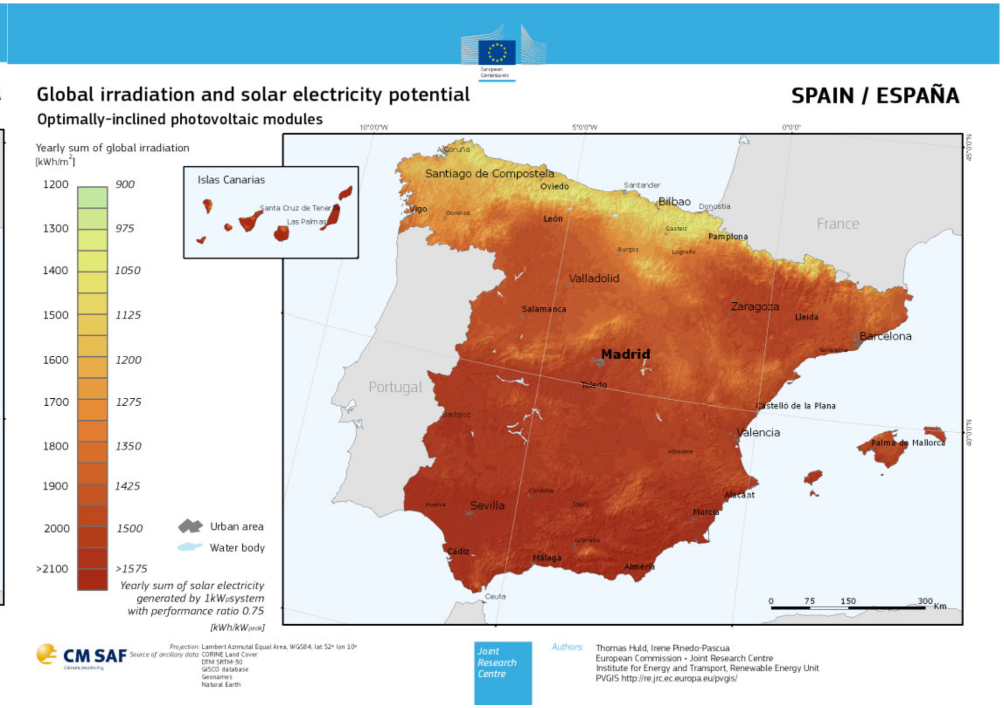
Šúri M., Huld T.A., Dunlop E.D. Ossenbrink H.A., 2007. Potential of solar electricity generation in the European Union member states and candidate countries. Solar Energy, 81, 1295–1305, http://re.jrc.ec.europa.eu/pvgis/.
Huld T., Müller R., Gambardella A., 2012. A new solar radiation database for estimating PV performance in Europe and Africa. Solar Energy, 86, 1803-1815.

Annual value of horizontal irradiation and with the optimum inclination 1998-2011. kWh/m^2

Fixed horizontal



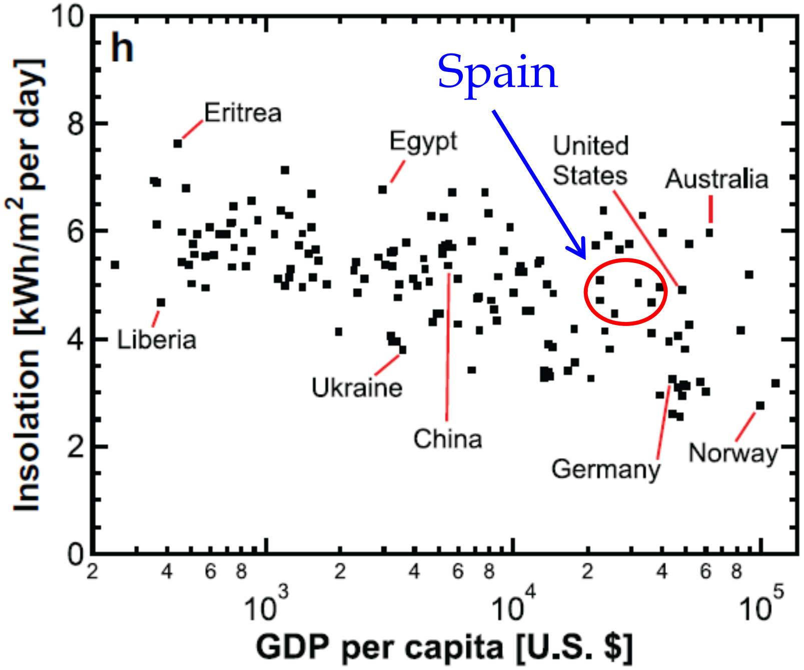
Fixed tilted



Potential Solar Electricity) [kWh/kWp] generated by a installed power of 1 kWp. Assuming System performance 0.75.

Potential electricity ≈ 1,400 kWh/m^2
Potential annual production 1% surface (5,000 km^2) 7,000 TWh
Energetic demand in Spain 1,500 TWh (5 times the energetic demand)

Daily Irradiation kWh/m2/day



Mean energy (Irradiation):

Germany ≈ 4 kWh/m²/day => 1460 kW/m2/year

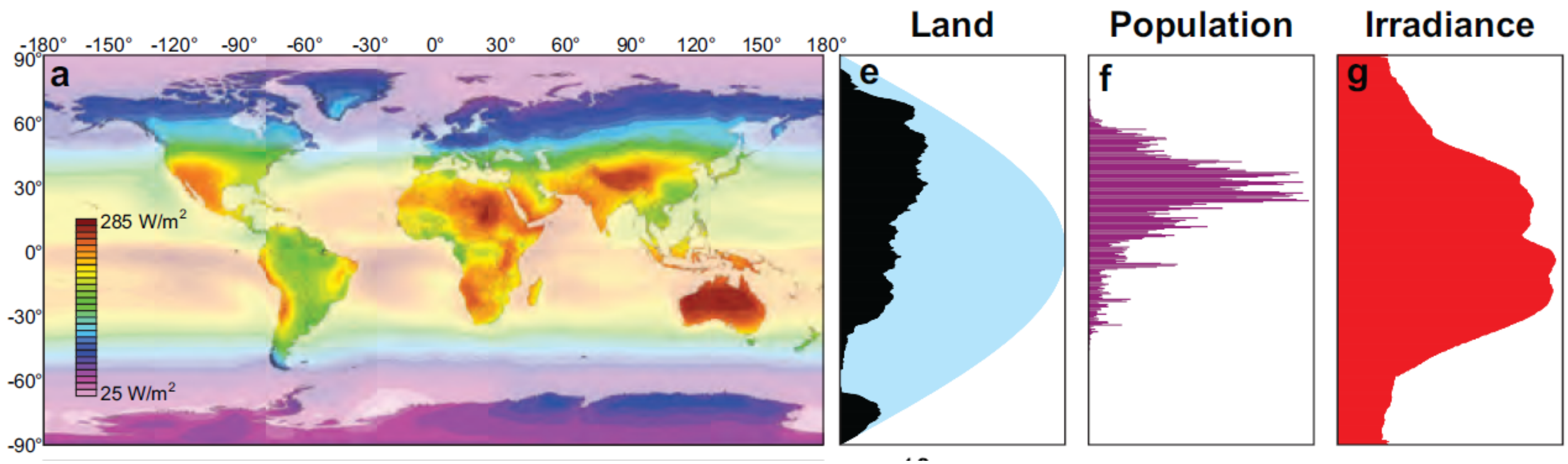
Spain ≈ 5 kWh/m²/day=> 1825 kW/m2/year

Australia ≈ 6 kWh/m²/day=> 2190 kW/m2/year

Irradiance 1000 W/m2

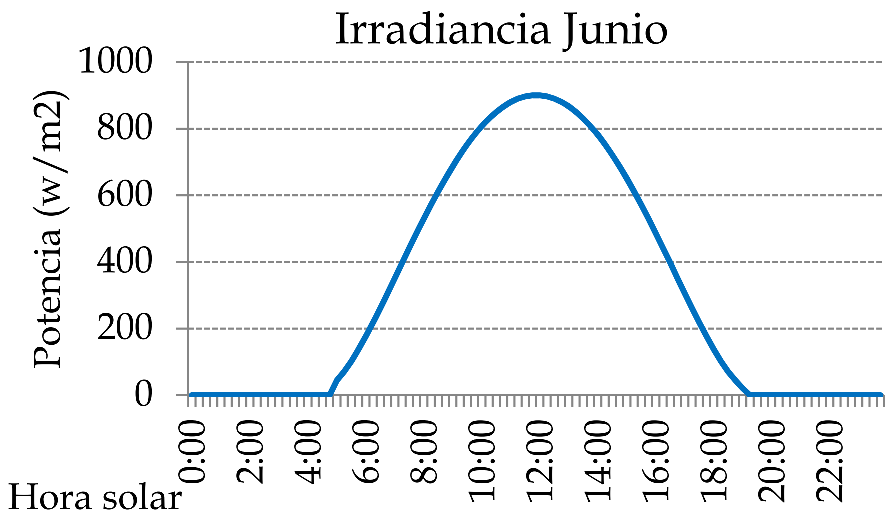
x sunny hours with maxime power:

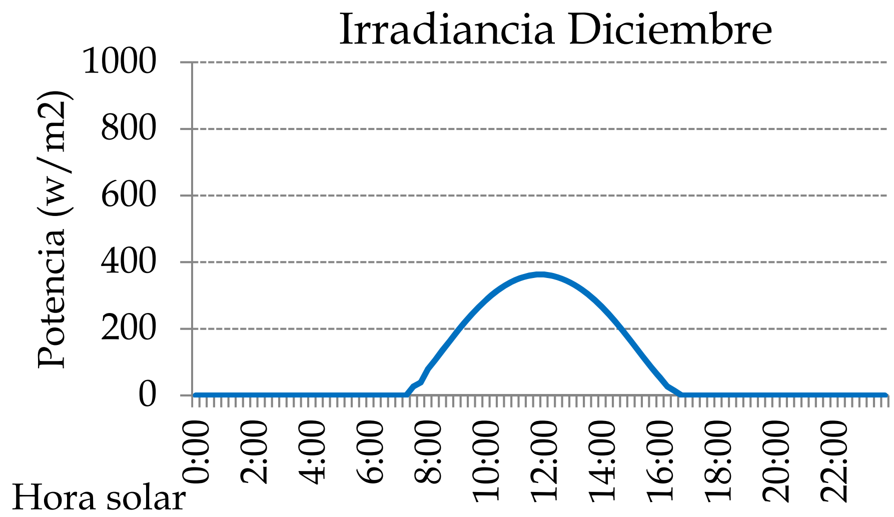
- Germany: 4 horas
- Spain: 5 horas
- Australia: 6 horas



Irradiance (Power)-Irradiation (Energy)

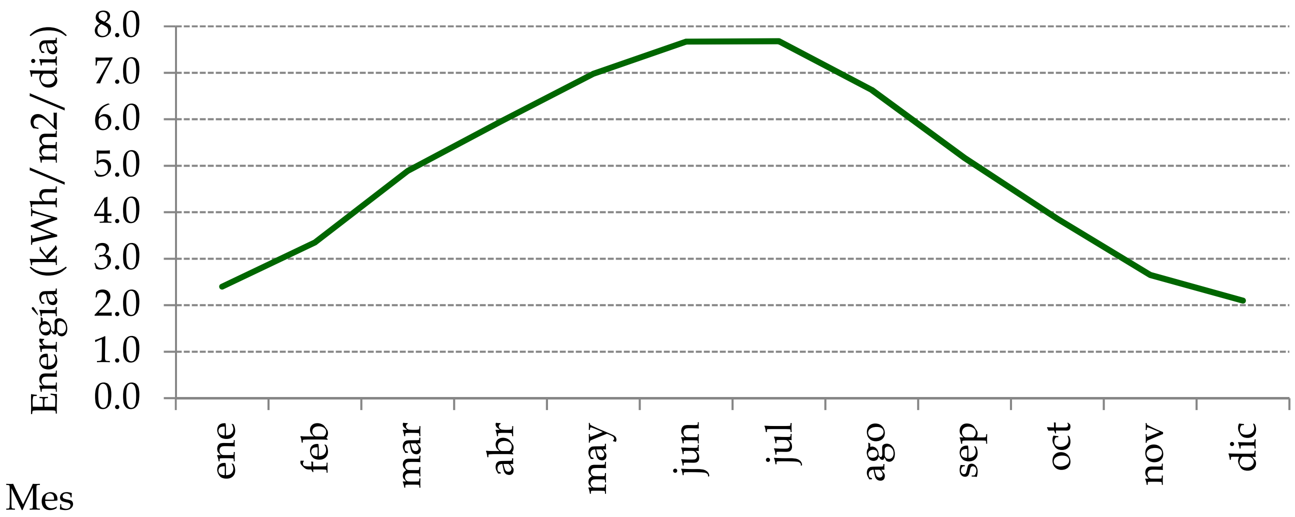
Valencia: fixed-horizontal (PV-GIS)





Irradiation (area) = 7616 Wh/m2-day = 7.6 kWh/m2-day

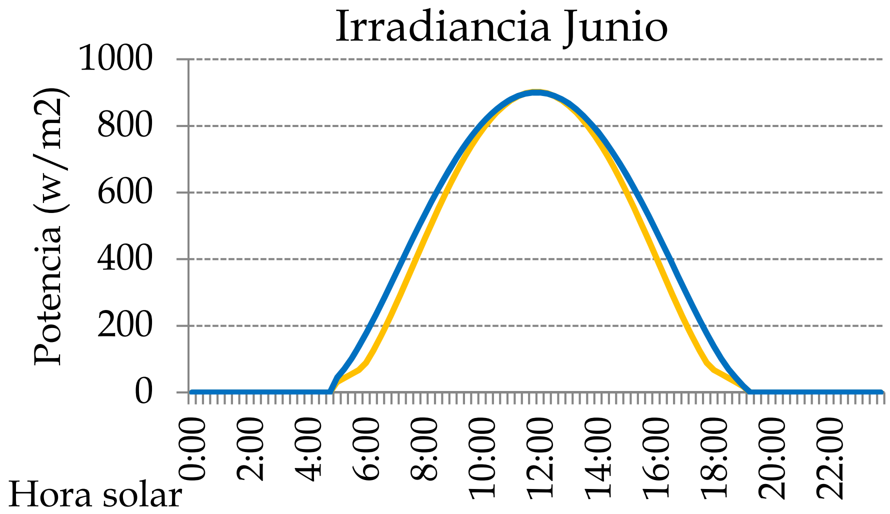
Irradiation (area) = 2074 Wh/m2-day = 2.1 kWh/m2-day

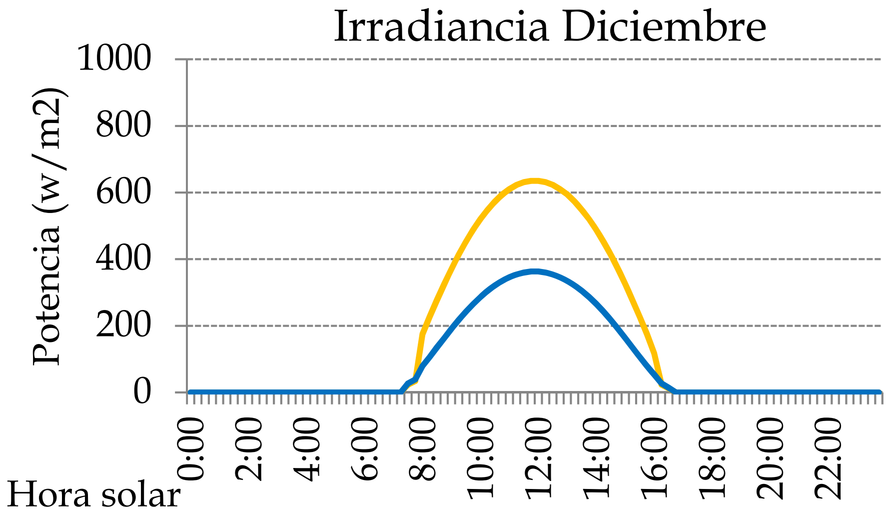


Mean irradiation (0º) = 5 kWh/m2-day (1800 kWh/m2-year)

Irradiance (Power)-Irradiation (Energy)

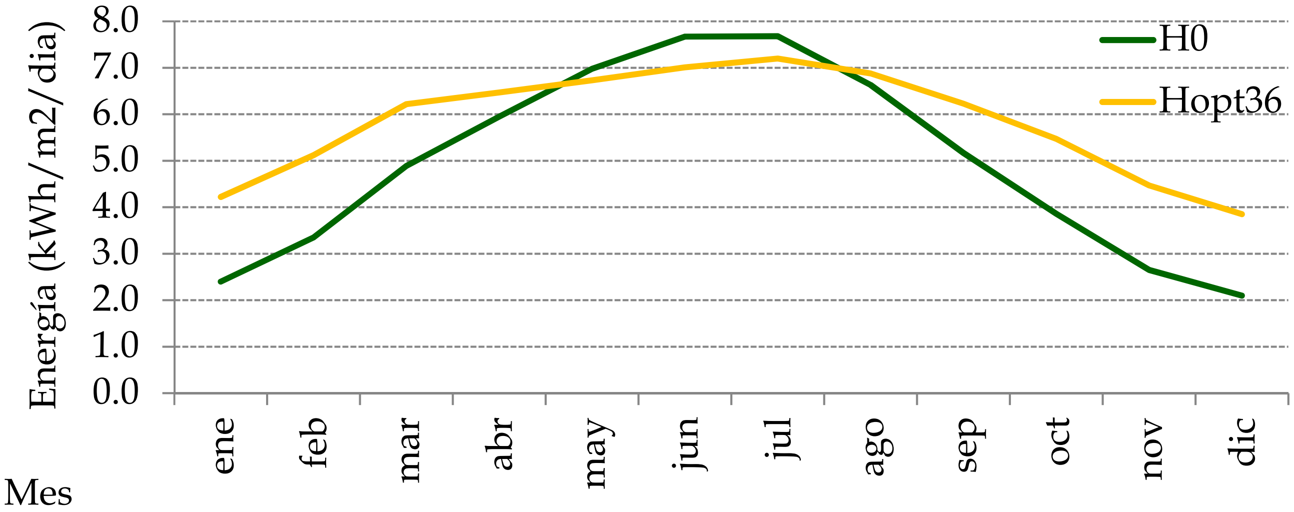
Valencia: tilted surface 36º opt (PV-GIS)





Irradiation (area) = 6955 Wh/m2-day
= 7.0 kWh/m2-day

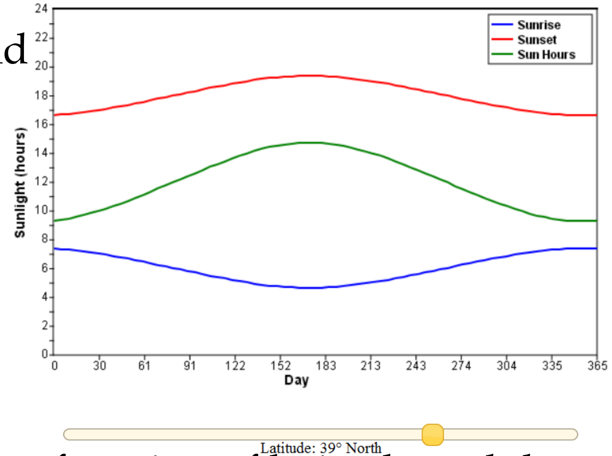
Irradiation (area) = 3783 Wh/m2-day
= 3.8 kWh/m2-day



Mean irradiation (36º)
= 5.8 kWh/m2-day
(2130 kWh/m2-year)

Irradiance (Power)-Irradiation (Energy)

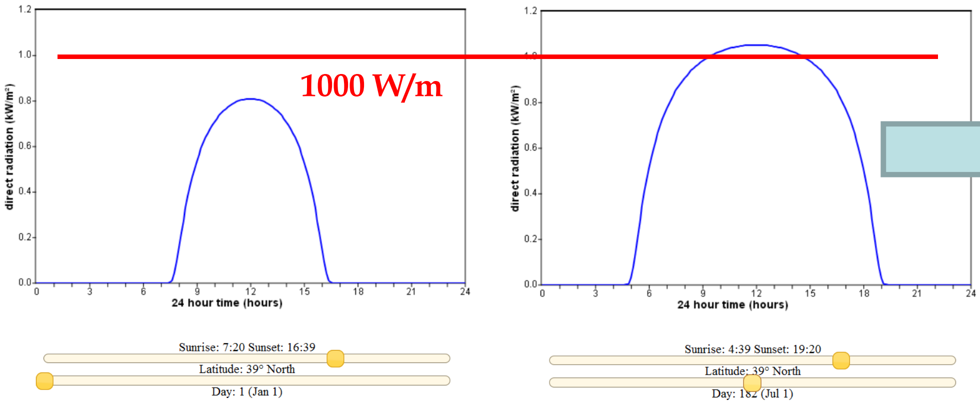
Sun hours, sunrise and sunset
- Function of the latitude

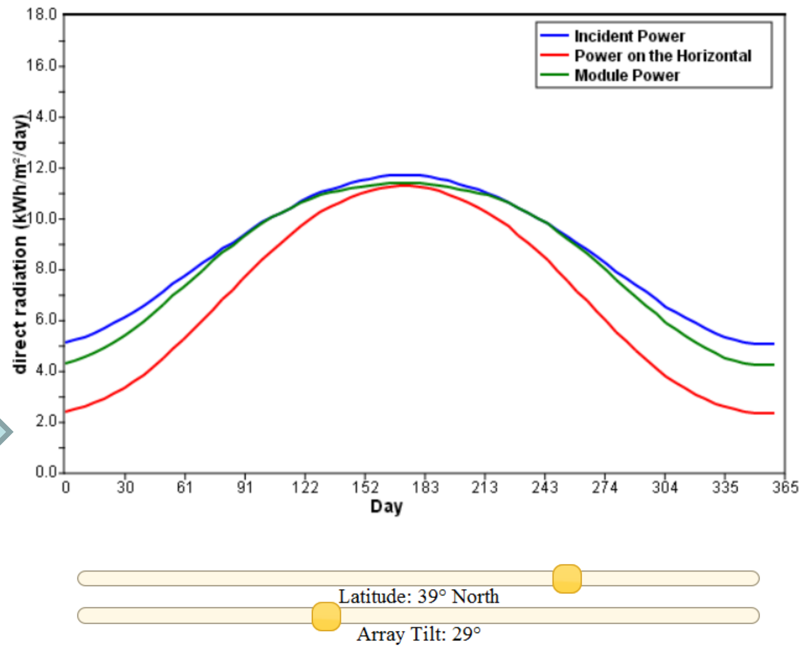


Daily Irradiation, tracking (blue).
- Fixed-tilted (green), angle= 29º
- Fixed-horizontal (red), angle =0

Irradiance in clear day : function of latitude and the day of the year

Winter: 1 january　　　Summer: 1 july





Latitude:

Madrid	40º 23′ Norte	Gijón	43º 32′ Norte
Valencia	39º 28′ Norte	Tarifa	36º 00′ Norte

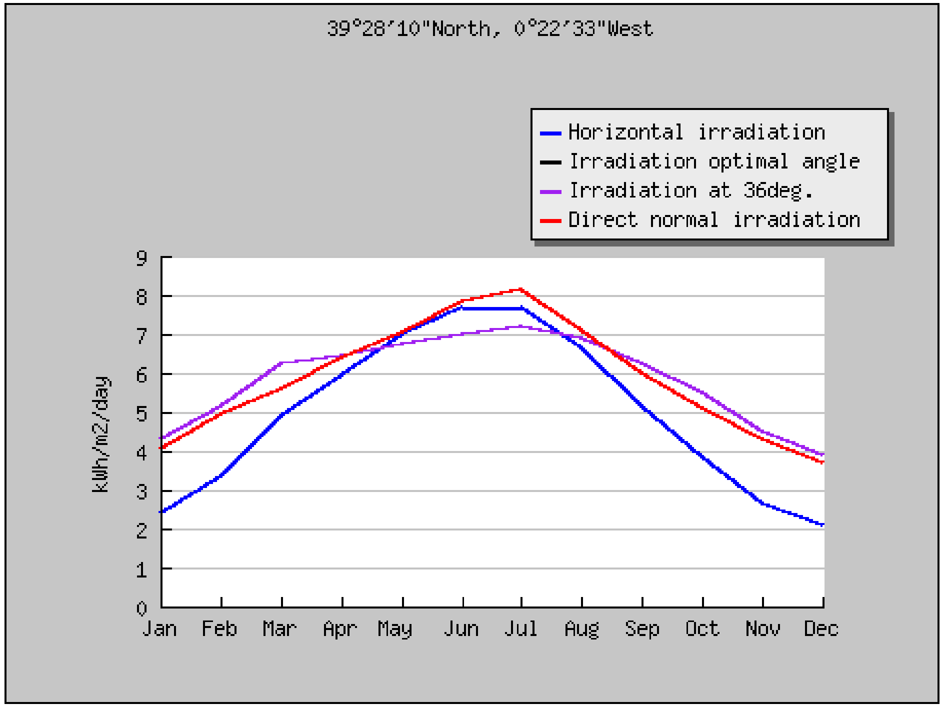
http://pveducation.org/pvcdrom/properties-of-sunlight/calculation-of-solar-insolation

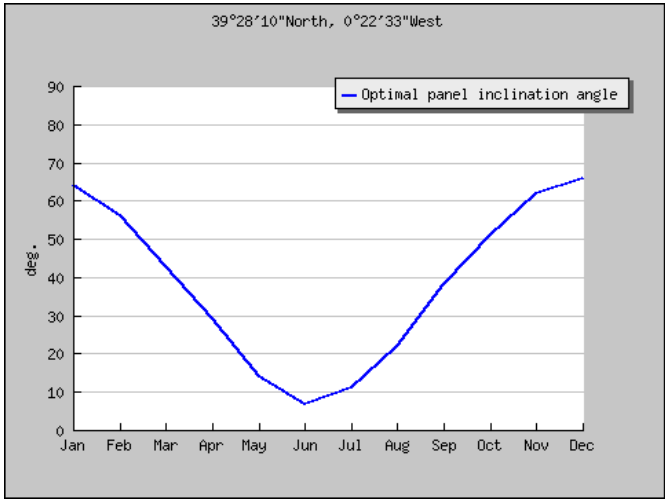
Solar Energy in Europa-PVGIS

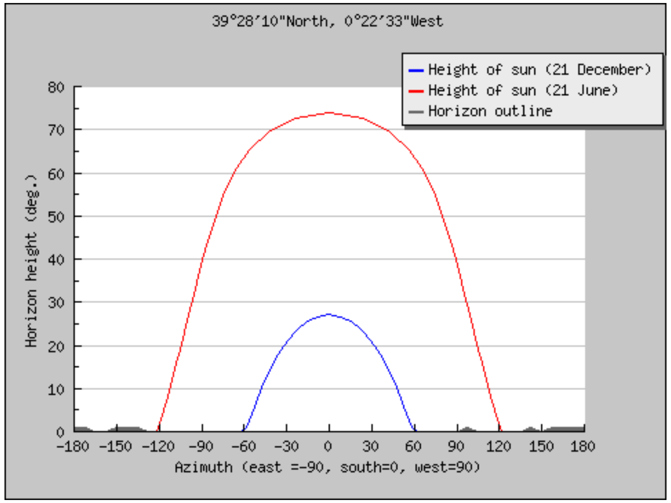
PV-GIS (Valencia, Latitude 39.5º):

Horizontal: 4.96 kWh/m2/day – 1,810 kWh/m2/year

Optima (36º): 5.85 kWh/m2/day - 2,135 kWh/m2/year



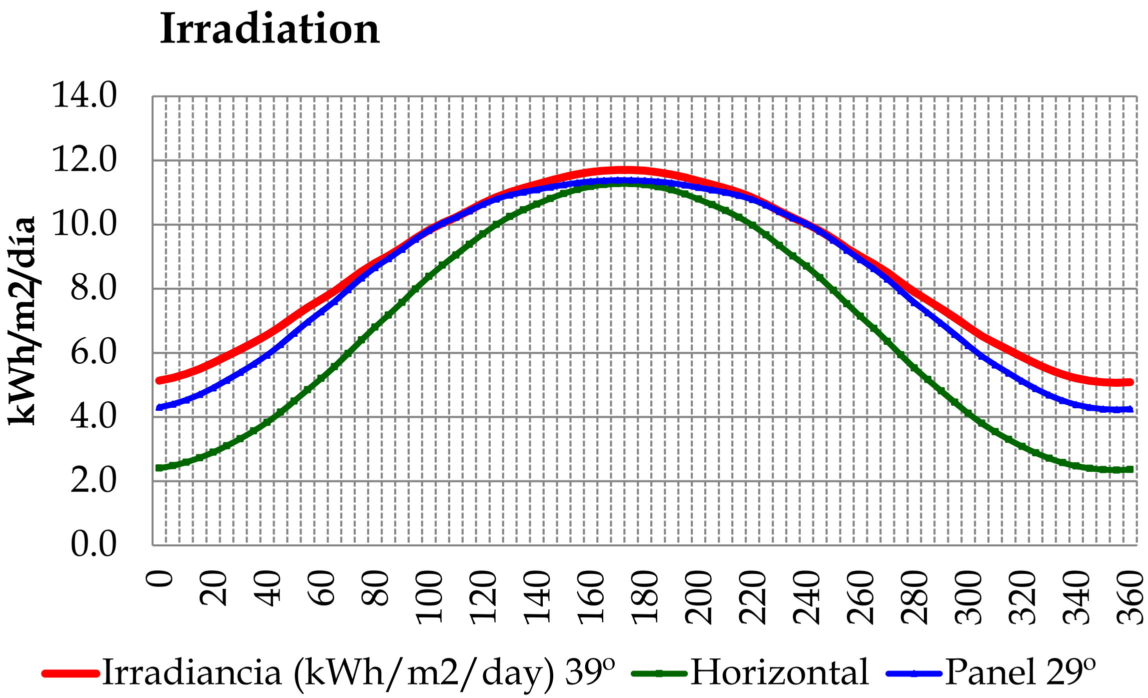




http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#

Daily/Yearly Irradiation

Irradiance=> Power: energy that reaches in each instant
Irradiation=> Energy: volume of energy accumulated in a day or in a year

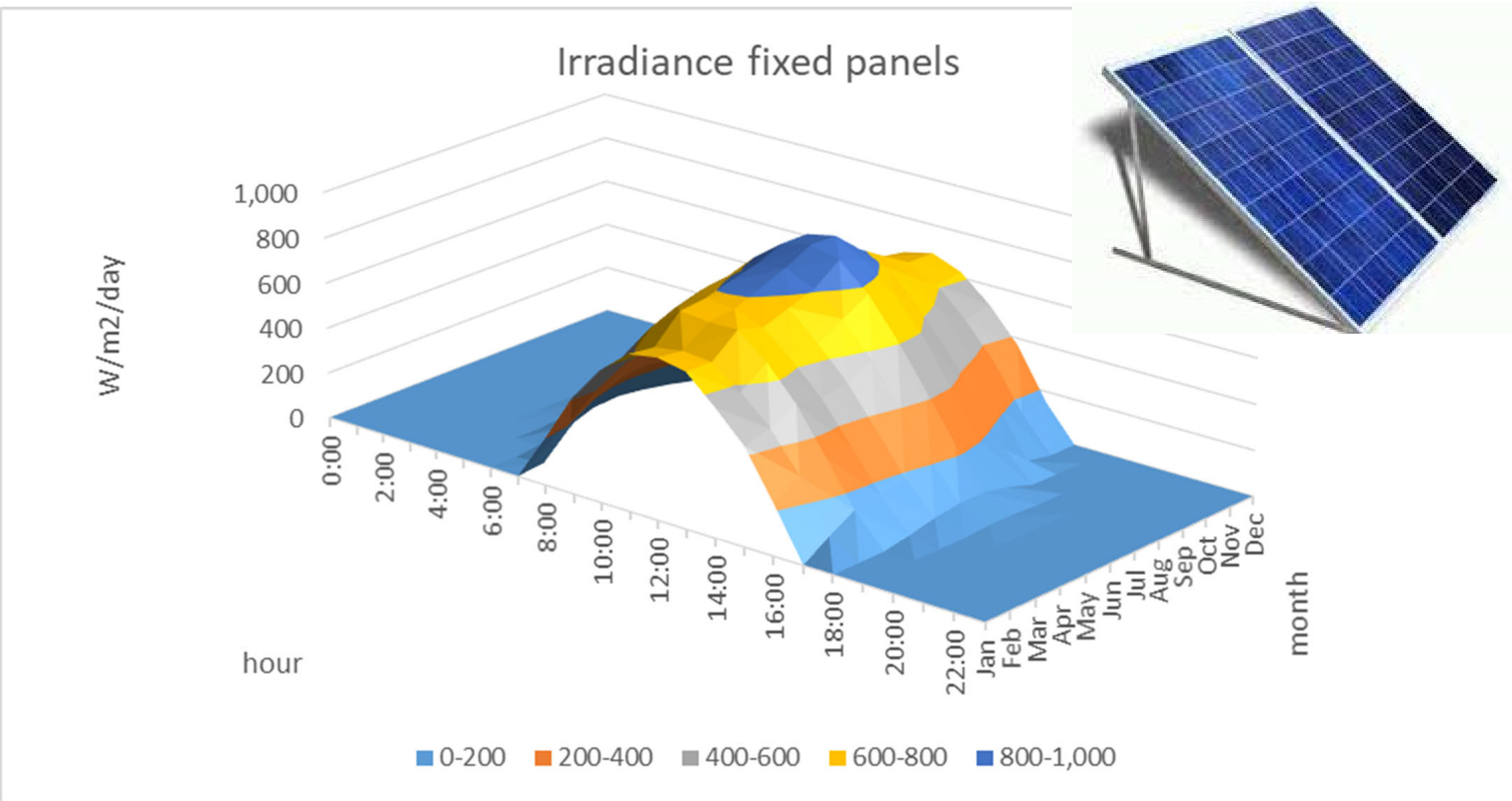


Latitud 39º (Valencia)
Values in a clear day:

- Daily Irradiation:
- 8.6 kWh/m2/día
- Yearly Irradiation:
- 3144 kWh/m2-año

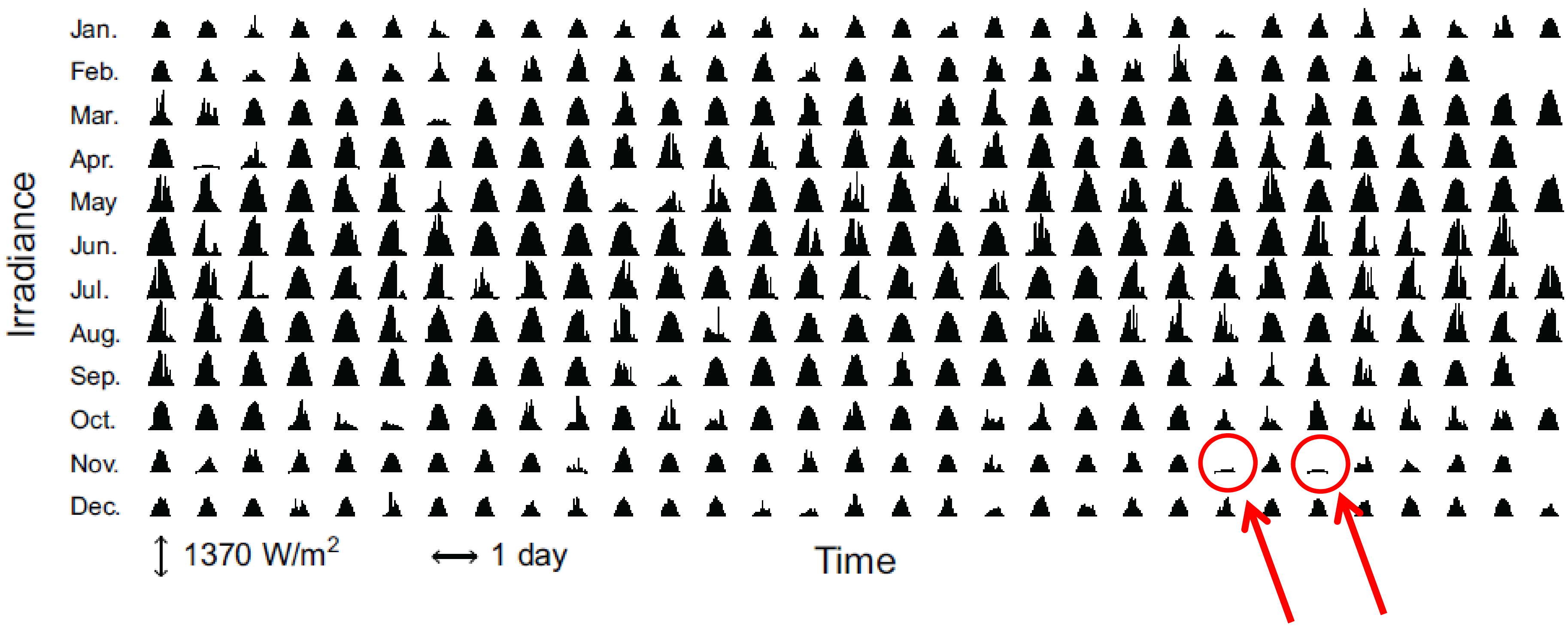
	Incoming Lat 39º	Horizontal	Tilted 29º
Daily Irradiation kWh/m2/day	8.6	6.8	8.2
Annual Irradiation kWh/m2-year	3,144	2,493	3,011
efficiency	0.75	0.75	0.75
Potential energy kWh/m2-year	2,358	1,870	2,258

Irradiance optimal angle



Irradiancie kW/m2

Solar energy throughout the day for a full year
There are days with almost zero irradiance all day.
Need of connection to the network or the use of accumulators



Complete Solar Irradiance Profi le in Golden, Colorado for the Year 2012