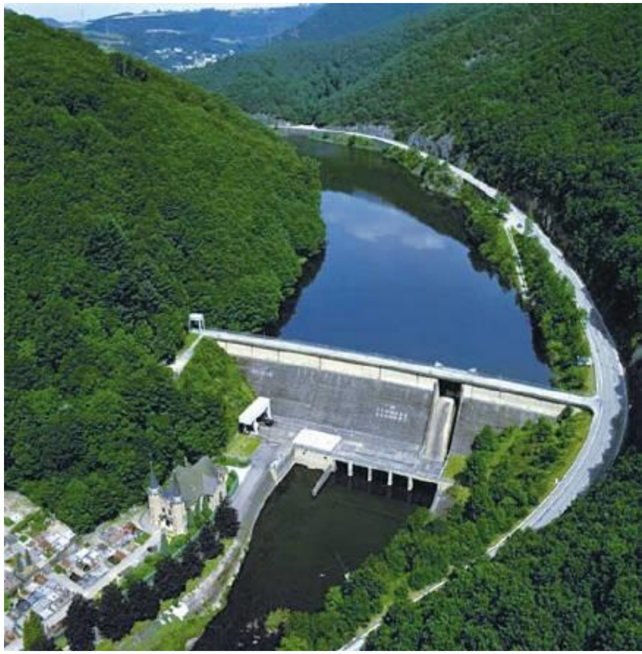
L4-online continued 3/3/2021

Renewable Energy and Photovoltaic Power Systems (ENEE5307)

L4- Emissions



Instructor : Nasser Ismail

Overview

- Solar Spectrum
- Atmospheric Effects
- Greenhouse Gases
- CO_2 Emissions
- Emissions Calculations
- Other Emissions

بدون تفاصيل كثيره

Solar Spectrum

- The sun provides energy needed to sustain life in our solar system
- In one hour, the earth receives enough energy from the sun to meet its energy needs for nearly a year
- i.e. this is ~5000 times the input to the earth’s energy from all other sources
- To optimize the utilization of the sun, it is useful to understand its properties

Solar Irradiance (power)

- Earth receives ~ 170 million GW of power from the sun
- Solar irradiance is the power of solar radiation per unit area usually (w/m^2)
- Since irradiance is power which is (rate of energy) then it is instantaneous value
- ***Solar irradiance is used as reference condition to evaluate the output performance of PV modules and solar energy equipment***
- Distance from the sun has great effect according to the inverse square law (at twice distance from sun , radiation is only ¼ th)

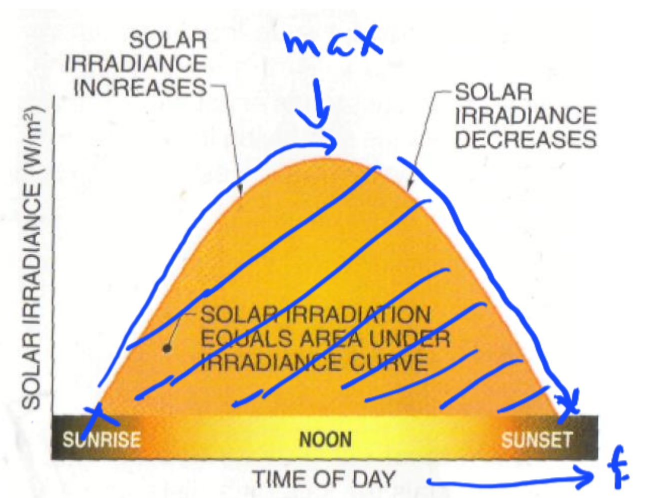
Solar Irradiation(Energy) Wh/m2

irradiance (Power) W/m2

- Solar irradiation; is the total amount of solar energy accumulated on an area over time which can be hour/day/week/month/year
- Solar irradiation expressed in Wh/m^2 or kWh/m^2 (amount of energy received on a surface over time)
- **Solar irradiation is the principal data for sizing and estimation performance of PV systems**

Solar irradiance and irradiation

- Greater irradiance (power) means energy is accumulated faster, which results in greater solar irradiation (total energy)
- On surface of earth, magnitude of irradiance changes throughout the day, starts at zero during nighttime, peaks at noon and down to zero again
- Irradiation : equals the area under irradiance curve
- Irradiation in Wh/m^2
- Irradiance in W/m^2



Extraterrestrial Solar Radiation

- Extraterrestrial Solar Radiation is solar radiation just outside Earth's atmosphere

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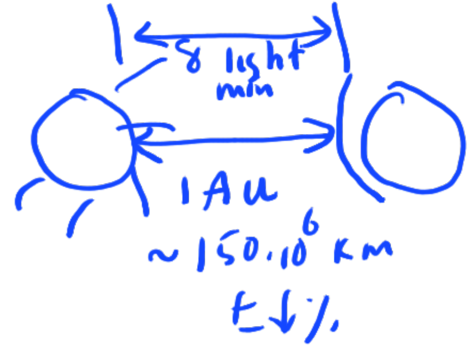
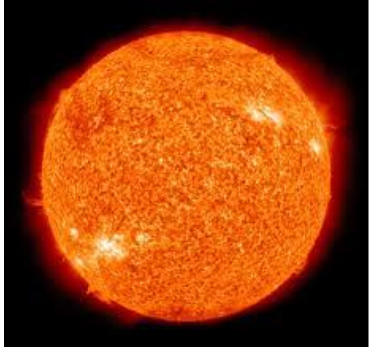
- AKA (also known as) top-of-atmosphere (TOA) radiation
- This quantity is very important in PV design and to understand how atmosphere affects solar power

The Solar Constant



- In space, solar power remains constant for a given distance from the sun since there is no atmosphere to scatter and absorb the energy
- The solar constant is the average extraterrestrial solar power (irradiance) at a distance of 1 AU (astronomical Unit) from the sun which has a value of ~ 1370 W/m^2 (calculated later)
- This value can vary by few % during the year
- ***An AU is approximately 93 million miles (150 million km). It's approximately 8 light-minutes.***
- ***More exactly, one astronomical unit (AU) = 92,955,807 miles (149,597,871 km***

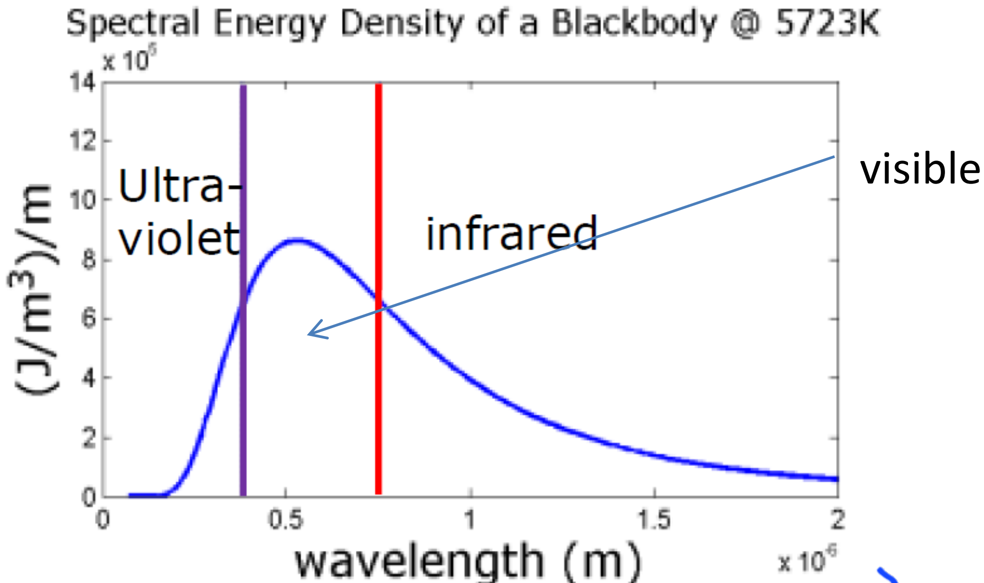
Nuclear fusion of hydrogen nuclei into helium



- Sun is composed of mixture of gases, the main one is hydrogen
- The sun converts Hydrogen to Helium in massive thermonuclear reaction and mass is converted to energy according to Einstein's formula $E=mc^2$ where (m- is mass and c - is speed of light)
- As a result surface of sun is maintained at 5800 K, and this energy is radiated a way from the sun in all directions in close agreement to Planck's blackbody radiation formula
- ***The Sun fuses 620 million metric tons of hydrogen each second.***

Solar Spectrum

- What is the frequency of the solar radiation?
  - Determined by Planck's Law
  - Relates temperature to energy at each frequency



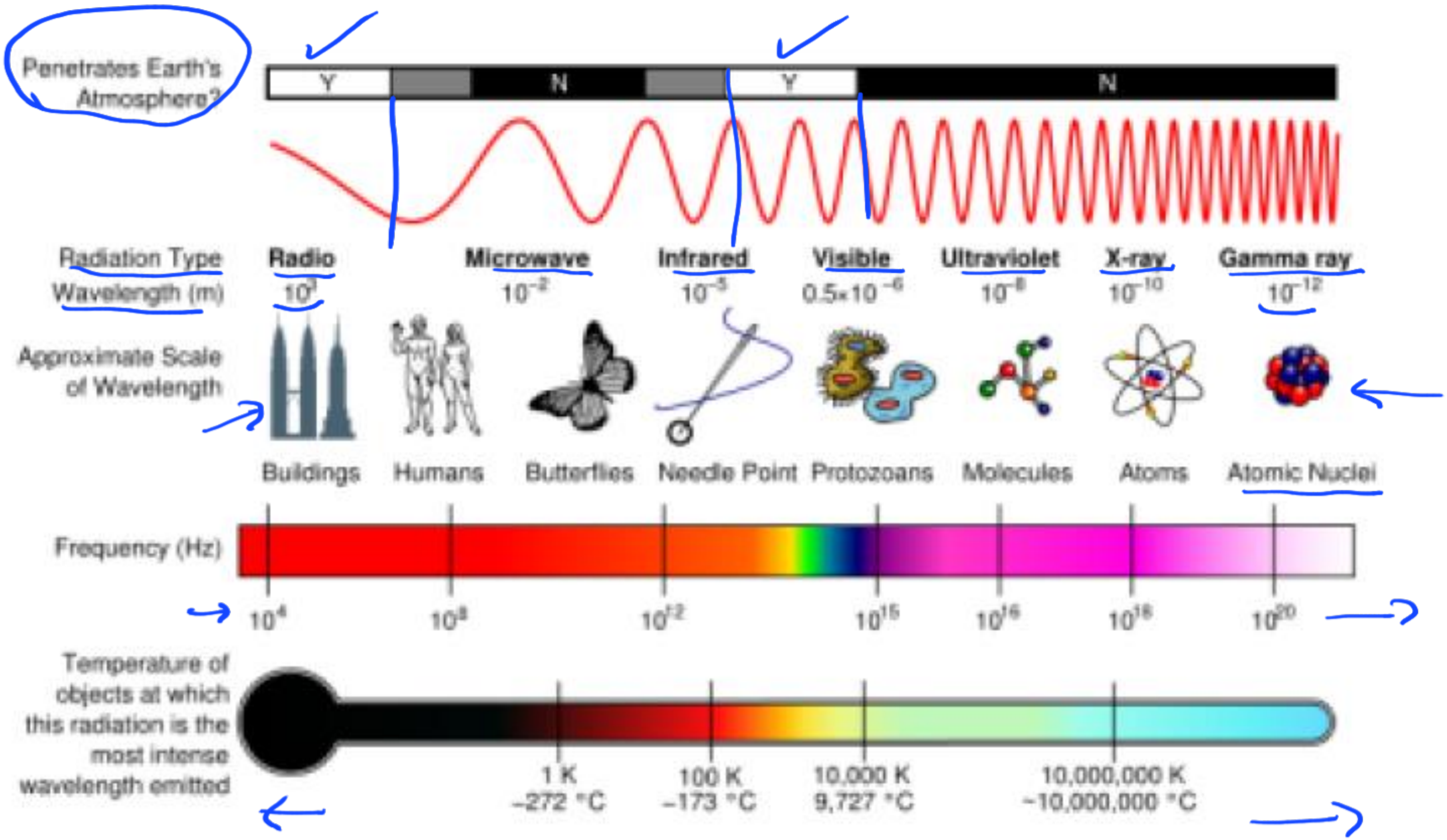
Energy is distributed across a spectrum of frequencies (or wavelengths)

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

Where : c - speed of light , λ - wavelength

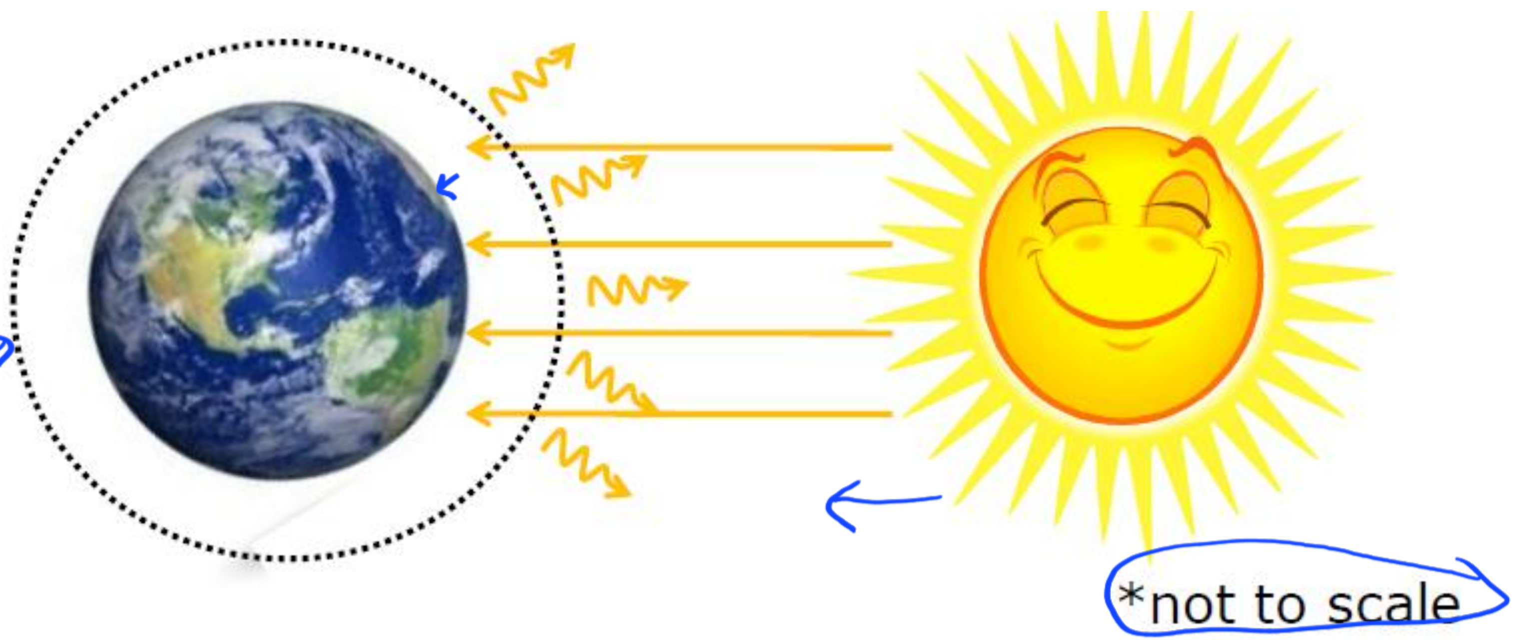
Higher frequency radiation contains more energy

Solar Spectrum



Atmospheric Effects

- Earth receives radiation from the sun with wide range of wave lengths 250-5000nm
- Atmosphere reflects about 30%
- Not all wavelengths are reflected equally



Atmospheric Effects

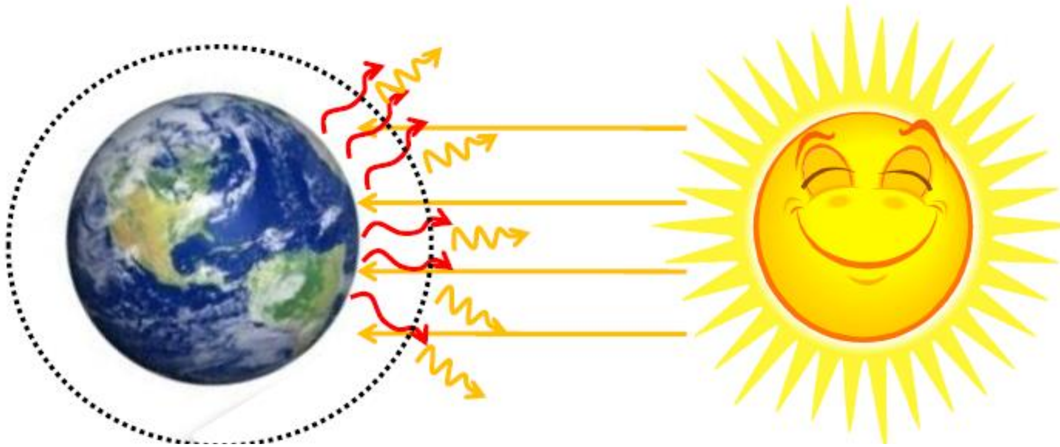
top of the atmosphere

Figure 3.8 The spectral power distributions of solar radiation corresponding to Air Mass 0 and Air Mass 1.5. Also shown is the theoretical spectral power distribution that would be expected, in space, if the sun were a perfect radiator (a 'black body') at 6000 °C

Source: Renewable Energy: Power for a Sustainable Future, G. Boyle

Atmospheric Effects

- Earth's surface heats and re-radiates heat back into space
  - Longwave infrared radiation



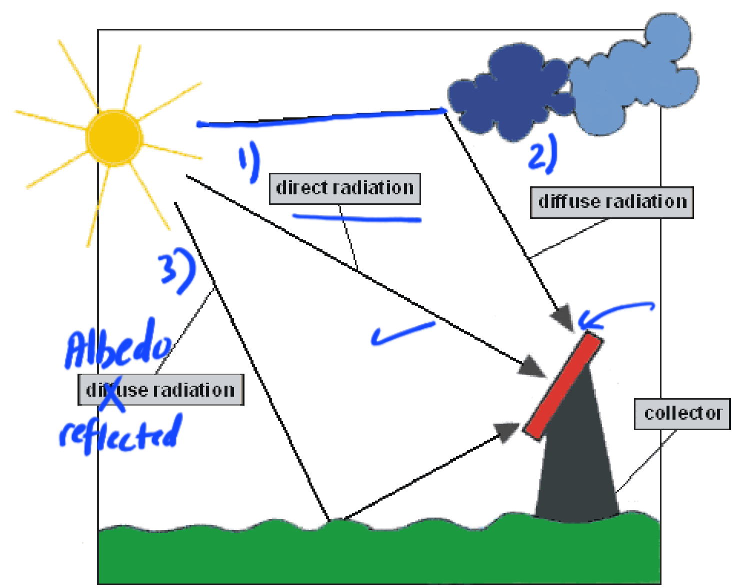
- Atmosphere blocks some of this radiation from being re-radiated back to space
- Atmosphere keeps the temperature on the surface at 15 °C on average
- Without the atmosphere the average surface temperature would be -18 °C

Global Radiation

Consists of:

- Direct Beam Radiation: Sunlight that reaches Earth without scattering is called direct or beam radiation
- Diffuse Radiation: scattered sunlight (due to clouds)
- Albedo Radiation: sunlight reflected from the ground

All three types form what is known as global radiation

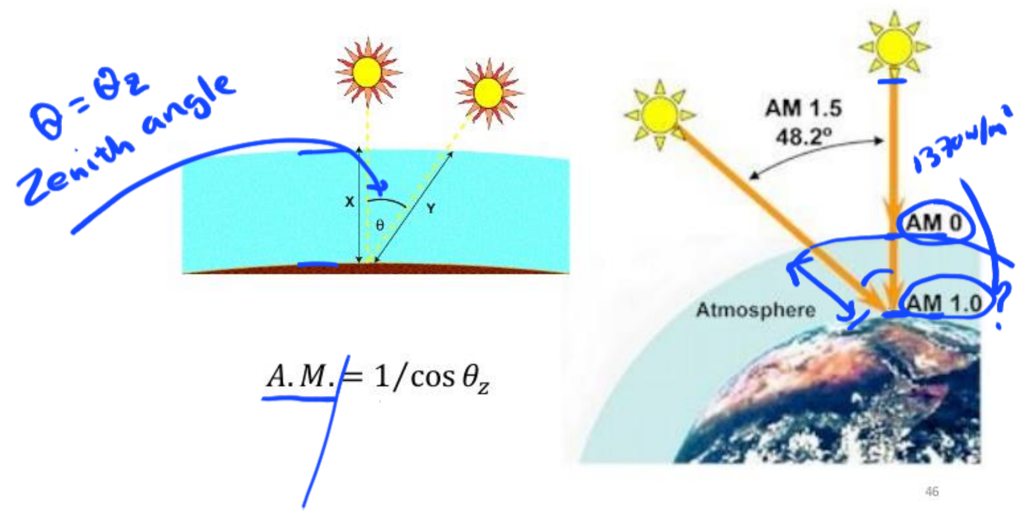


direct radiation + diffuse radiation = global radiation

- The amount of sunlight either absorbed or scattered depends on the length of the path through the atmosphere
- **This path length is compared with** a vertical path directly to sea level, which is designated as **air mass** =1 (AM1)
- Air mass at higher altitude will be less than 1 for sun directly overhead, and the air mass generally will be more than unity for non-vertical sun angles

Chapter #2: Solar Geometry

Air mass

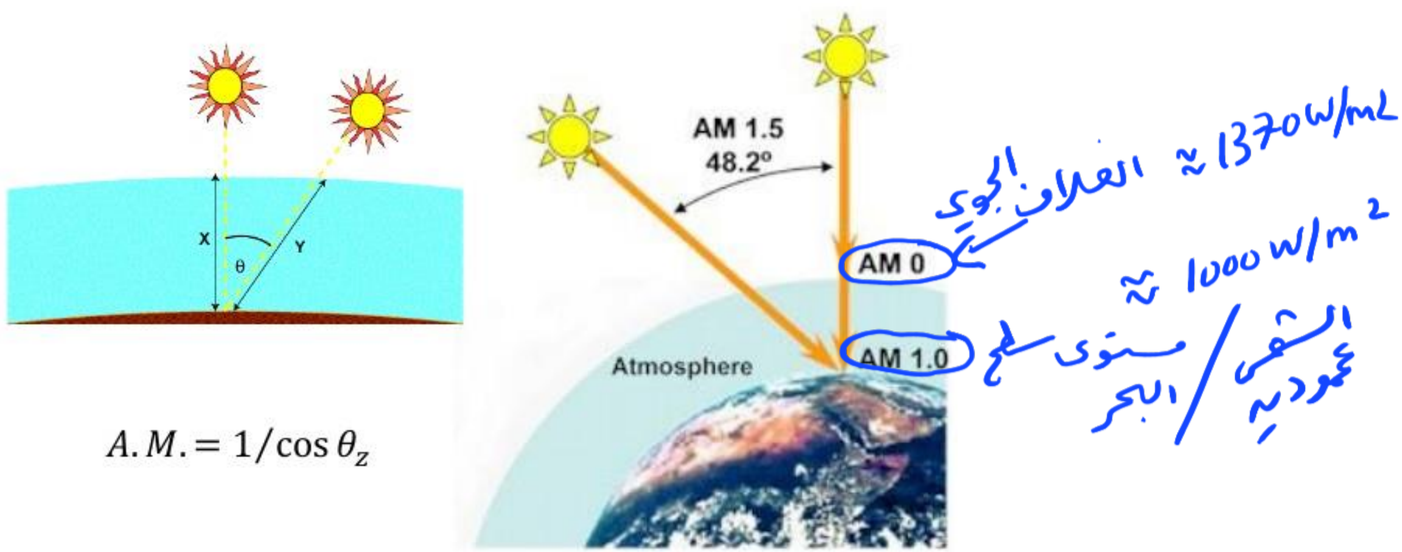


$$A.M. = 1/\cos\theta_z$$

- In general **the air mass** through which sunlight passes depends on zenith angle (θz) which is the angle between direct beam and the vertical beam
- At AM1 (sea level) the global radiation is reduced from 1367 w/m^2 to ~ 1000W/m^2 which is almost equal to 0.7 the value at AM0 (top of atmosphere)

1367 -1370

Air mass



$$A.M. = 1/\cos\theta_z$$

- On the average , over the surface of the earth , an amount of heat is reradiated into space at night that is just equal to the amount absorbed from the sun during the day
- As long as this balance (steady-state condition) is kept , the average temperature of the earth is kept constant
- If not the earth will heat up or cool down
- Volcanos can upset this balance by filling the atmosphere by with fine ash that reflects sunlight from earth (cooling down)
- Greenhouse gases such as CO_2 and methane tend to prevent the earth from reradiating heat at night (thus causing global warming)

End of L4 online 3/3/2021

Greenhouse Gases

- Atmospheric gases that keep the longwave infrared radiation from escaping are greenhouse gases
- **Common Greenhouse gases (GHG):**
  - **Water vapor (responsible for 60-80 % of greenhouse effect)**
  - **Carbon dioxide (CO_2)**
  - **Methane**
  - **N_2O**
  - **Ozone**

Greenhouse Gases

- Current CO_2 concentration ~ 380 ppm (parts per million)
  - 18th Century it was ~ 280 ppm
- Burning fossil fuels releases previously buried carbon into the atmosphere
- Concentration of CO_2 increases

Greenhouse Gases

- Different GHG contribute differently to the greenhouse effect
- Global Warming Potential (GWP)

  Ration of warming caused by 1 kg of GHG to 1 kg of CO_2

- GWP of some GHG:
  - CO_2:1
  - Methane : 21
  - N_2O: 310

CO_2 Emissions

- How much CO2 is released by burning a kg of Methane? Oil? Coal?

- First Consider Methane : CH4
  - 4 Hydrogen (atomic weight 1)
  - 1 Carbon (atomic weight 12)
- Total weight per methane molecule: 12+1+1+1+1=16
- Carbon makes 12/16 (75%) of the mass of methane
- 1 kg of methane contains 0.75 kg of carbon

CO2 Emissions

- Combustion reaction for methane:
  - $CH_4 + 2O_2 => CO_2 + 2H_2O$
- Atomic weight of Oxygen is 16
- The carbon in CO_2 makes up 27% of its weight (12/(2 x 16 + 12))
- To put it another way: for every 1kg of carbon combusted, 3.67 kg of CO_2 is released
  - 1/0.27 = 367%

نسبة ثاني اكسيد الكربون الناتج هو 367% من الكربون المستخدم

CO_2 Emissions

- If 1 kg of methane is combusted, how much CO_2 is released?
- 1 kg of methane contains 0.75 kg of Carbon
- Multiply by 3.67 , we get $0.75 \times 3.67 = 2.7$ kg of CO_2
- More CO_2 is released than there was methane

Emissions From Coal

- Coal contains more elements than hydrogen and carbon such as
  - Sulfur
  - Nitrogen
- Ratio of carbon mass to the molecular mass varies depending on type of coal
- A reasonable assumption range is 60-90%
  - Lignite on the lower end
  - Anthracite on the higher end

Emissions From Oil

- Emissions depend on the type of oil
- Consider $C_{16}H_{34}$
  - Ratio of carbon: (16 x 12)/(16 x 12 + 34) = 85%
- How much CO_2 is released when 1 kg of $C_{16}H_{34}$ is combusted?

- 1kg of $C_{16}H_{34}$ contains 0.85 kg of carbon
- 0.85 kg of carbon produces 3.11kg of CO_2 (0.85 x 3.67)

Emissions Calculation

- Usually we are interested in metrics such as kg of CO_2 emissions per kWh of energy or per gallon
- How many kg of CO_2 are released from one gallon of diesel fuel?
  - Assume 3 kg of diesel fuel per gallon

Emissions Calculation

- A back-of-the-envelope calculation:
  - Assume 3 kg of diesel fuel per gallon
  - 3 x 0.85 x 3.67 = 9.36 kg of CO_2/gallon

- Specific energy densities (approximate values shown)
  - Methane: 56 MJ/kg
  - Natural Gas: 53 MJ/kg
  - Coal: 15-30 MJ/kg
  - Diesel: 45 MJ/kg

Emissions Calculation

- Energy conversion efficiencies (approximate values shown)
  - Natural gas (Brayton cycle): ~25-35%
  - Coal (Rankine cycle): ~30-45%
  - Diesel (Diesel cycle): ~30-45%
- $E_{out} = \eta E_{in}$

- How much CO_2 is released in order to generate 1kWh of electrical energy using:
  - Natural gas (Brayton cycle, η = 30%)
  - Coal (Rankine cycle, η = 40%)

Emissions Calculation

- First compute how many kg of fuel are used:
  - 1kWh = 3.6MJ
  - Accounting for efficiency
    - E_{in} = 3.6/0.3 = 12 MJ
  - Using the specific energy density
    - $m_{nat\ gas}$ = 12/53 = 0.23 kg
- Compute the ratio of carbon:
  - m_C = 0.23 x 0.75 = 0.17 kg
- Next compute how many kg of CO_2 are produced:
  - m_{Co2} = 0.17 x 3.67 = <u>0.62 kg</u>

SOx

- Coal, Oil, natural gas contain impurities such as Sulfur and Nitrogen
- Sulfur Oxides cause acid rain, damage to plants, water supply and endanger respiratory health
  - $S + O_2 \Rightarrow SO_2$ (sulfur dioxide)
  - $2SO_2 + O_2 \Rightarrow SO_3$ (sulfur trioxide)
  - $3SO_3 + H_2O \Rightarrow H_2SO_4$ (sulfuric acid)
- Released on the order of
  - Coal: 7kg/MWh
  - Natural gas: 5kg/MWh

NOx

- NO_x causes
  - Smog
  - Acid rain
- Greenhouse gas
- Released on the order of 2kg/MWh