Sustainable Energy Transformation Technologies, SH2706

Lecture No 20

Title:
Environmental Effects of ETS

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Outline

- Affordable and clean energy
  - linkage energy-development-needs
  - linkage energy-air-water-land-material
  - greenhouse gas emission
  - key role of sustainable development goal 7 (SDG 7)
- Climate and greenhouse effect
- Environmental effects of various ETS

Social and Economic Development Needs

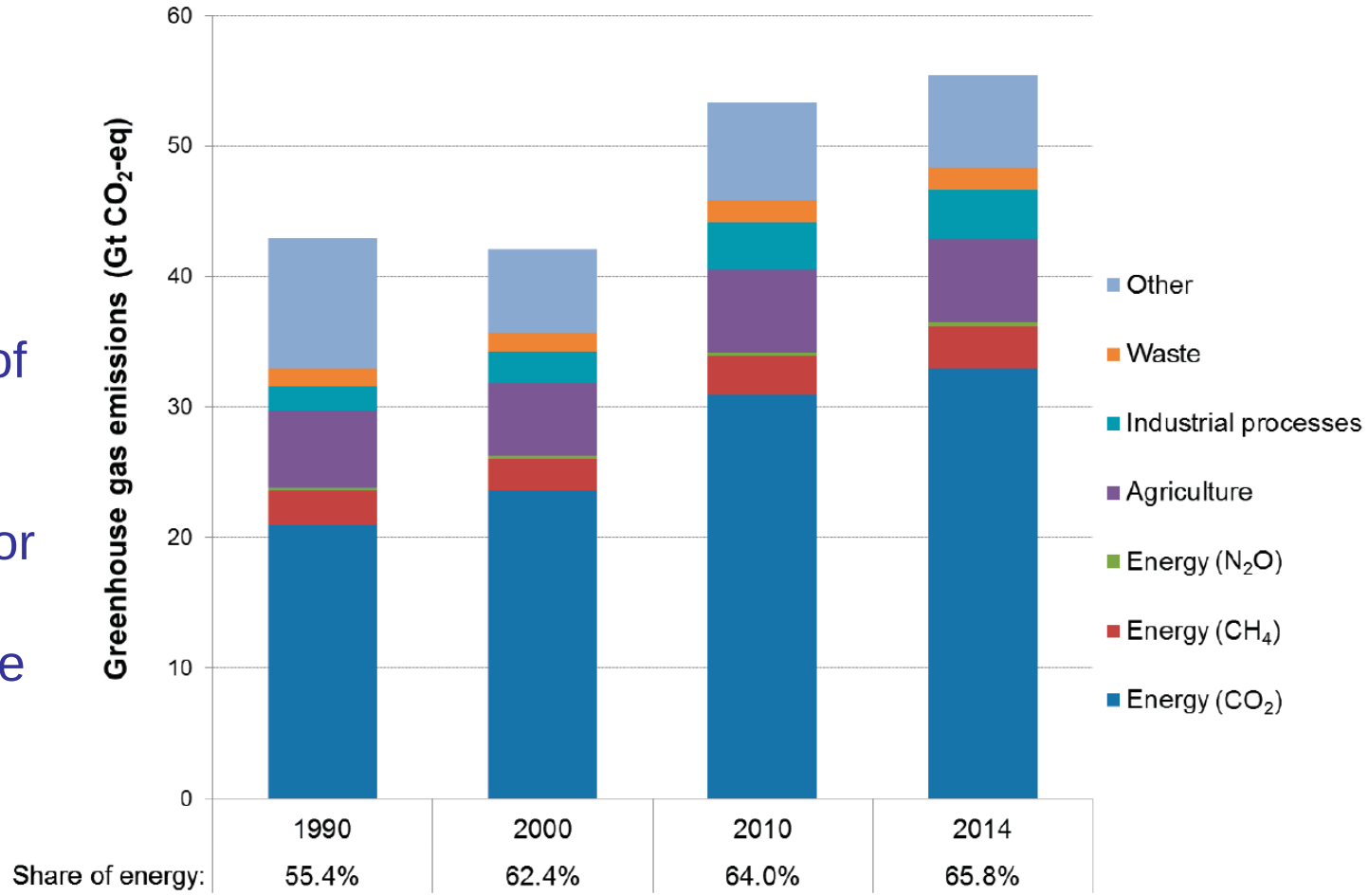
- Shelter, including heating, cooling, lighting
  - electricity, natural gas, kerosene, construction materials, etc
- Food and nutrition
  - fertilizer production, agricultural machinery, food processing
- Health and education
- Clean water and sanitation
  - electricity for pumping, desalination, water supply
- Mobility
  - road and other transportation, vehicles, fuels, minerals, metals
- Employment, poverty reduction
  - all energy uses

Energy-air-land-water-material

- Human energy transformations include production and usage of various energy forms
- These transformations incur negative changes into several environmental factors, such as air, land, water and material; in particular
  - greenhouse gases and other pollutants are emitted into the atmosphere causing global warming, as well as acidification and eutrophication of water and land
  - land is occupied and often destroyed
  - water resources are used and/or polluted
  - materials (minerals) are used
- The dominant issue that the world is facing today is the climate change due to **emission of greenhouse gases**

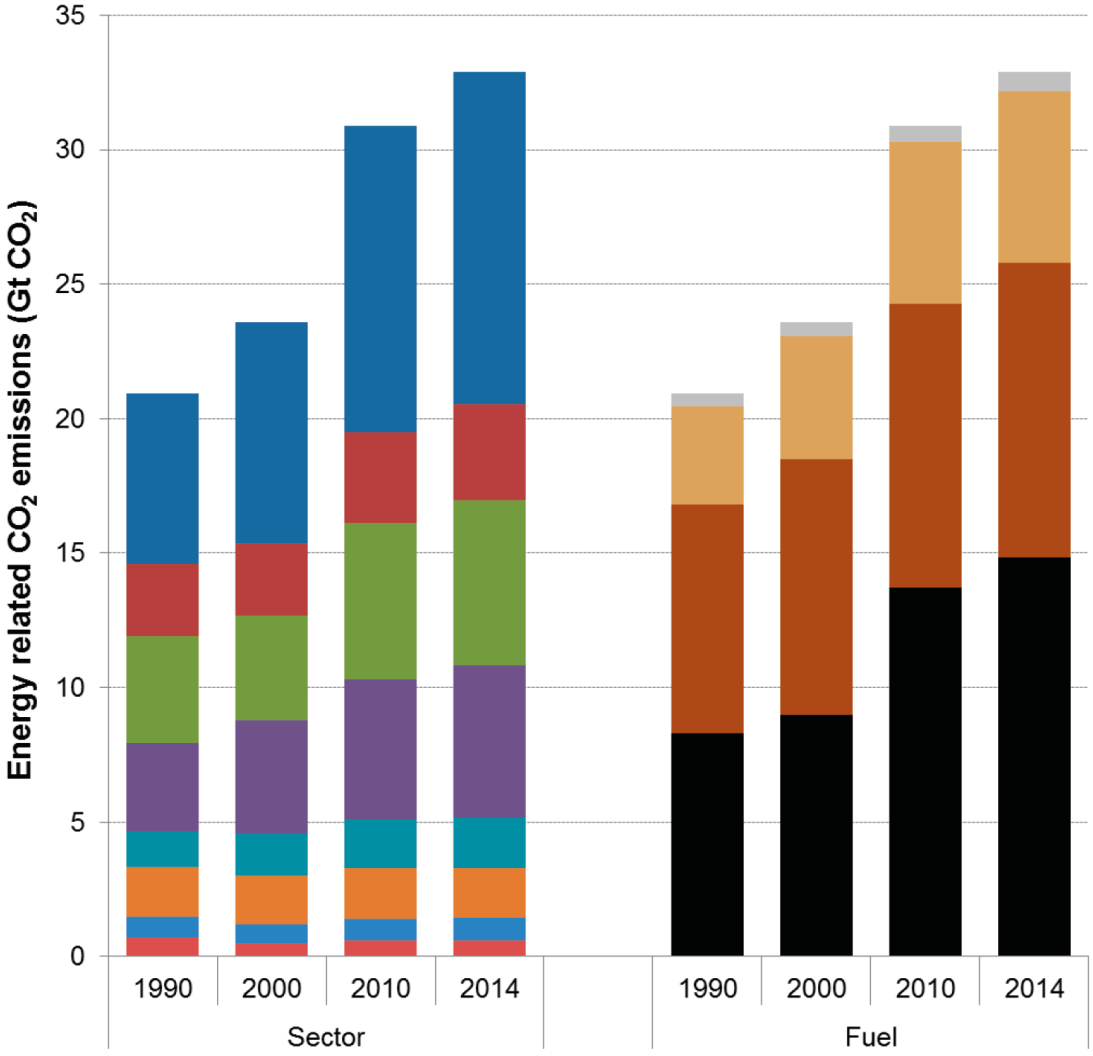
Greenhouse Gas Emissions (1)

Human transformation of energy (both harvesting and use) accounts for almost 2/3rd of total greenhouse gas (GHG) emissions



Gt CO_2-eq – gigatons of carbon dioxide equivalent; CH_4 – methane, N_2O – nitrous oxide. Source: IAEA 2018

Greenhouse Gas Emissions (2)



Sector
- Electricity generation
- Other energy industry (incl. heat)
- Manufacturing and construction
- Road transport
- Other transport
- Residential
- Services
- Other sectors

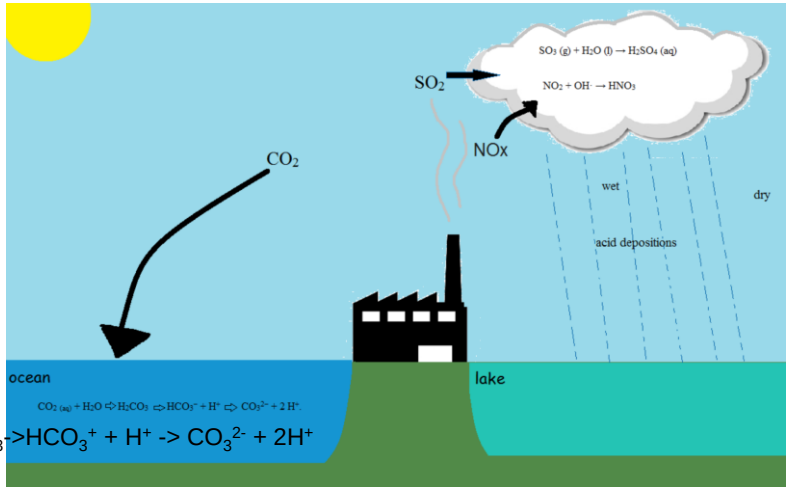
Fuel
- Other and fugitive
- Natural gas
- Oil
- Coal, peat and oil shale

CO_2 from energy transformation is emitted across a range of sectors and activities

Gt CO_2 – gigatons of carbon dioxide. Source: IEA 2017

Acidification (1)

- Ocean, freshwater and soil acidification:
- Ocean acidification: ongoing decrease in the pH of the Earth's oceans caused by the uptake of carbon dioxide CO_2) from the atmosphere
- Freshwater acidification is caused by acid rains (low pH). Fish and other aquatic animals will die in water with low pH

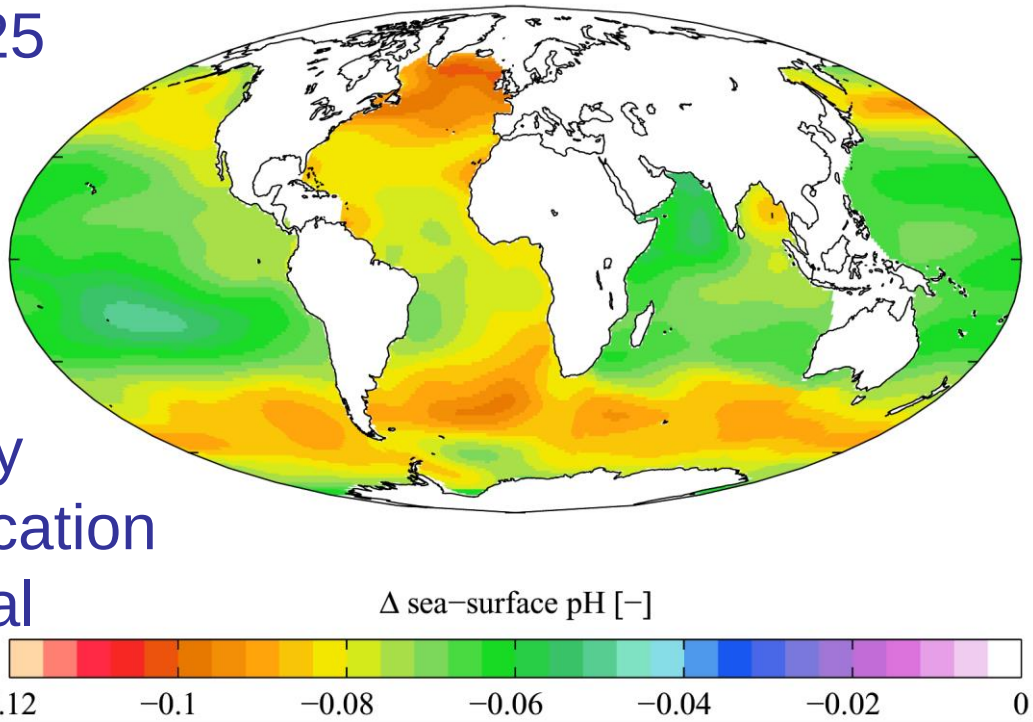


$CO_2+H_2O->H_2CO_3->HCO_3^+ + H^+ -> CO_3^{2-} + 2H^+$

- soil acidification is the build-up of hydrogen cations reducing the soil pH; mainly due to nitric acid (HNO_3) and sulfuric acid (H_2SO_4) which are present in acid rain

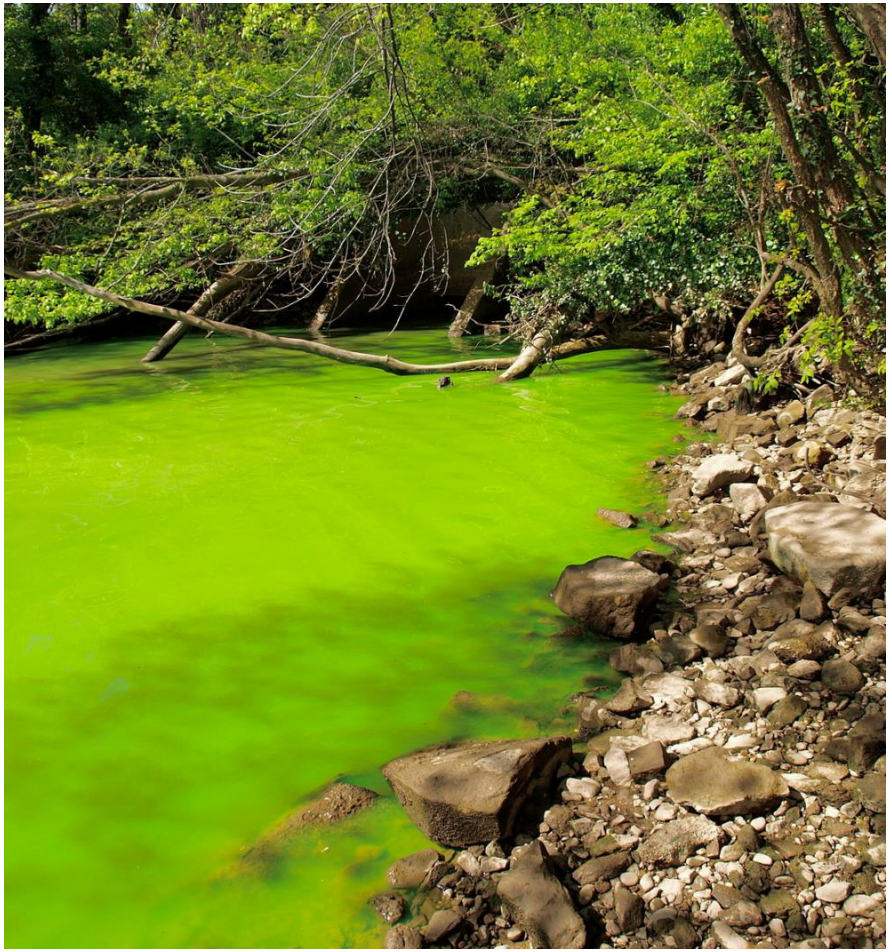
Acidification (2)

- pH- measure of acidity – is proportional to negative base-10 logarithm of the density of H^+ ions
- Over recent several hundred years, pH of ocean water has decreased from 8.25 to 8.14 **Potentially harmful for marine organisms**
- This corresponds to 30% increase in concentration of H^+ ions
- Seawater is thus slightly basic (pH>7), so acidification is making it more neutral (not acid)

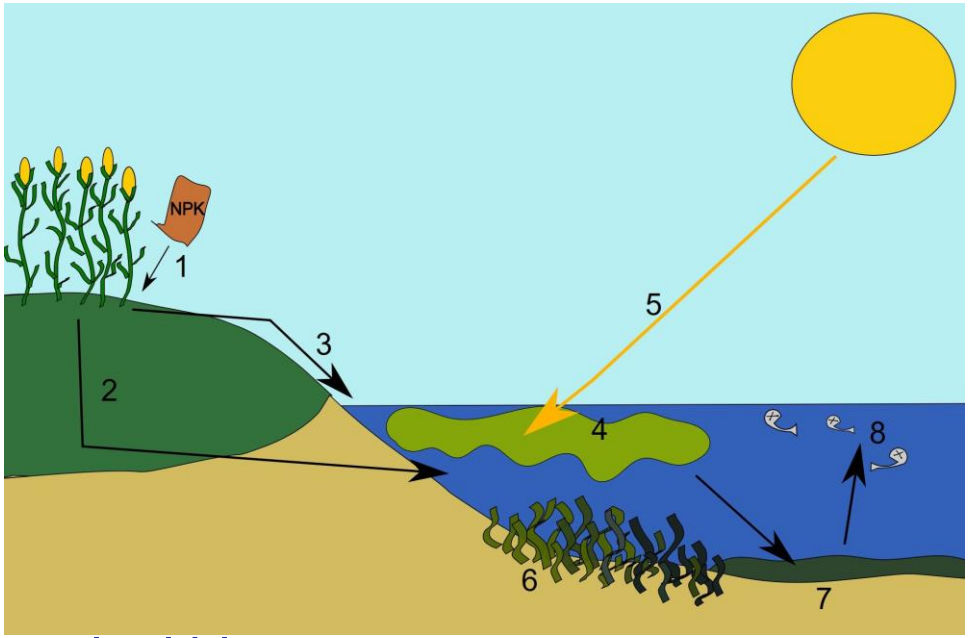


Eutrophication (1)

- Eutrophication occurs when a body of water becomes overly enriched with minerals and nutrients that include excessive growth of plants and algae
- This process may result in oxygen depletion of the water body
- Example is “bloom” in a water body due to increased levels of nutrients



Eutrophication (2)



- 1) Excess nutrients are applied to the soil
- 2) Some nutrients leach to the soil where they can remain for years. Finally they can drain to a water body
- 3) Some nutrients run off over the ground into the water body
- 4) The excess nutrients cause an algal bloom
- 5) The algal bloom blocks the sunlight from reaching the bottom
- 6) The plants beneath the algal bloom die due to lack of the sunlight
- 7) Algal bloom dies and sinks to the bottom. Bacterial decomposition starts
- 8) The decomposition depleats the water of oxygen. Fish suffocate

Key Role of SDG 7

Affordable energy reduces poverty (SDG 1) and inequality (SDG 10), and supports health (SDG 3), education (SDG 4), industry (SDG 9) and economic growth (SDG 8)

Reliable energy is essential for industry (SDG 9), agriculture (SDG 2), health (SDG 3) and education (SDG 4)

Energy for all fosters peace and justice (SDG 16), and partnerships (SDG 17)

Modern energy supports clean communities (SDG 11), health (SDG 3) and gender equality (SDG 5)

Sustainable energy is crucial for climate action (SDG 13), ecosystems (SDG 14, 15), agriculture (SDG 2), water (SDG 6, 14) and reducing waste (SDG 12)

Source: IAEA 2017

Achieving SDG7 can support all other 17 SDGs

Climate (1)

- Weather in a given region is described by meteorological parameters such as temperature, humidity, wind, cloud formations and precipitation, either instantaneous or averaged over a few hours or a few days
- Climate is described by the same parameters averaged over many years
- The climate of the Earth has been fluctuating for billions of years, largely driven by solar and volcanic forcing
- Anthropogenic (resulting from human activity) influence on the atmosphere has become visible since year 1750
- During that time the atmospheric concentration of CO_2 has increased from 278 to over 400 parts per million

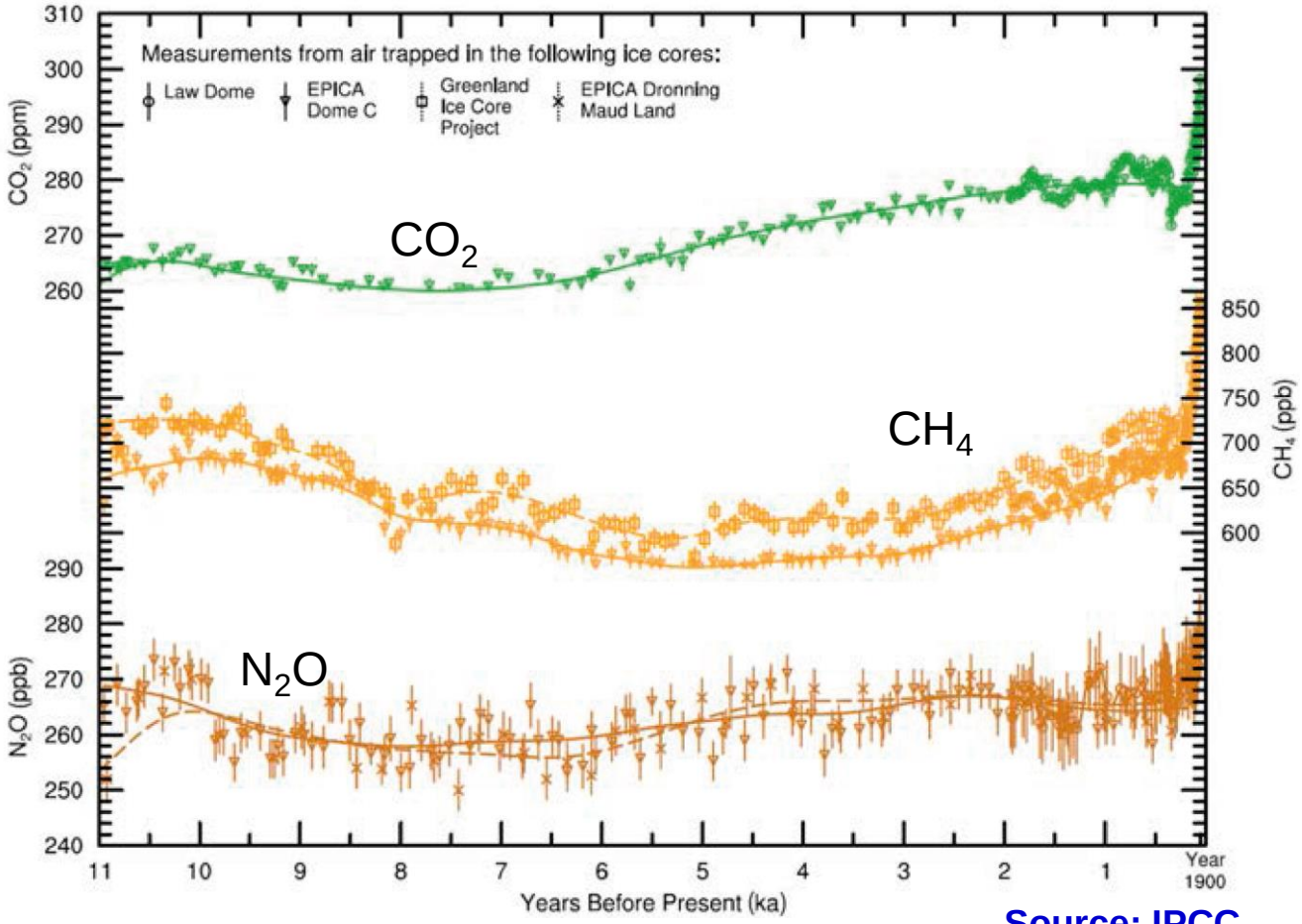
Climate (2)

- As a result of elevated concentrations of CO_2, CH_4 (methane) and N_2O (nitrous oxide) the warming of the atmosphere and oceans is observed
- Human induced contribution to the observed global mean surface temperature between 1951 and 2010 is estimated to 0.5 ÷ 1.3 K
- The Intergovernmental Panel on Climate Change (IPCC) has prepared four scenarios to project the future global temperature change
  - according to three of the scenarios the global mean temperature is projected to exceed 2 K by 2100
  - only drastic reduction of emissions by 2050 can prevent this

Climate (3)

- The Paris Agreement (adopted in 2015 and enforced in 2016) aims at that the increase in global average temperature should not exceed 2 K relative to the preindustrial level

CO_2, CH_4 and N_2O in Holocene

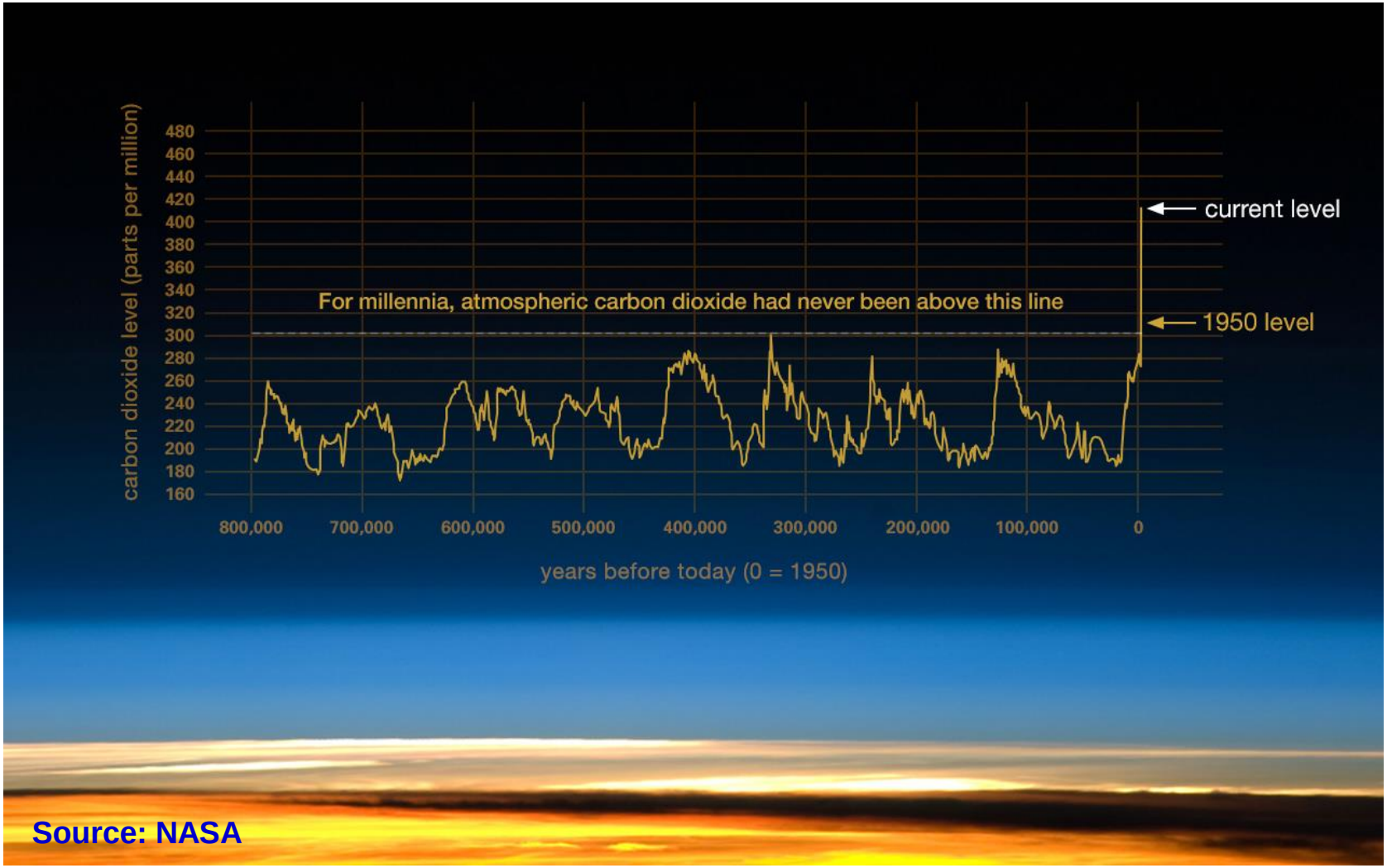


Source: IPCC

We can observe that concentrations of CO_2, CH_4 and N_2O was varying slowly during last 11 thousand years, before 1750. Significant shift can be seen during present time, after 1750.

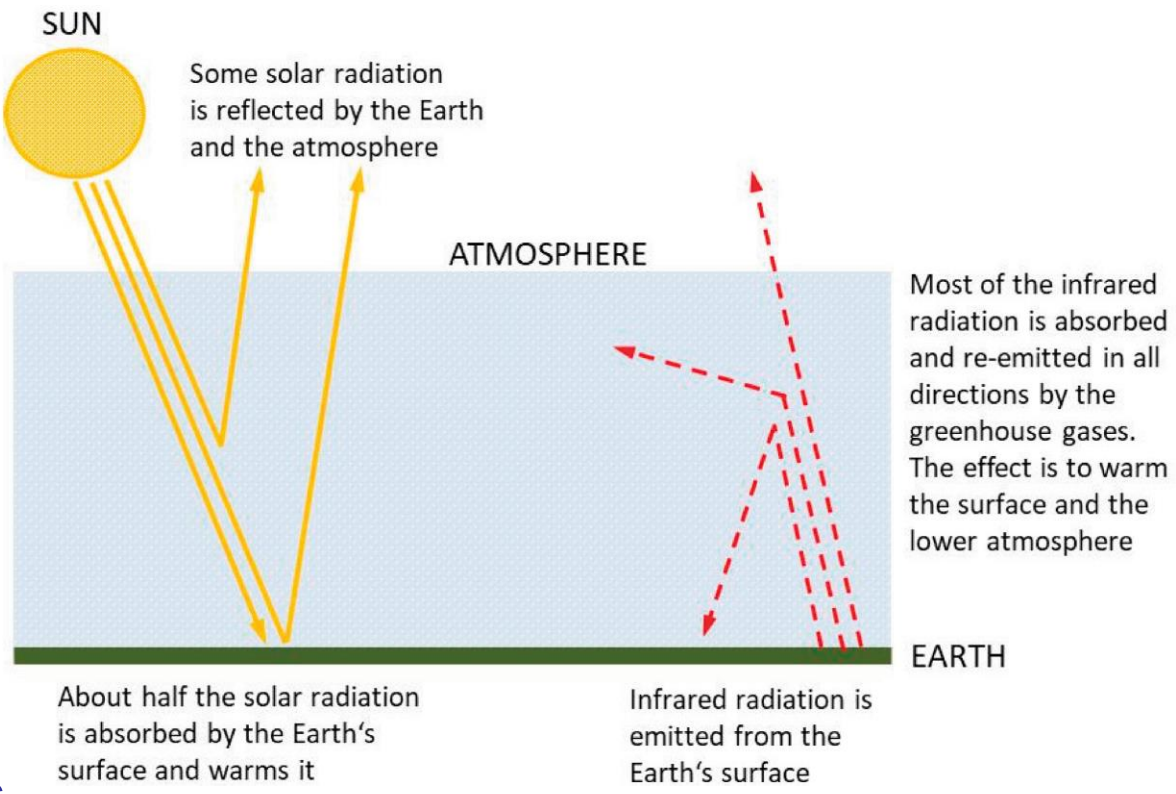
ka – 1000 years
ppm – parts per million
ppb – parts per billion

CO_2 history: 800 ky ago till now



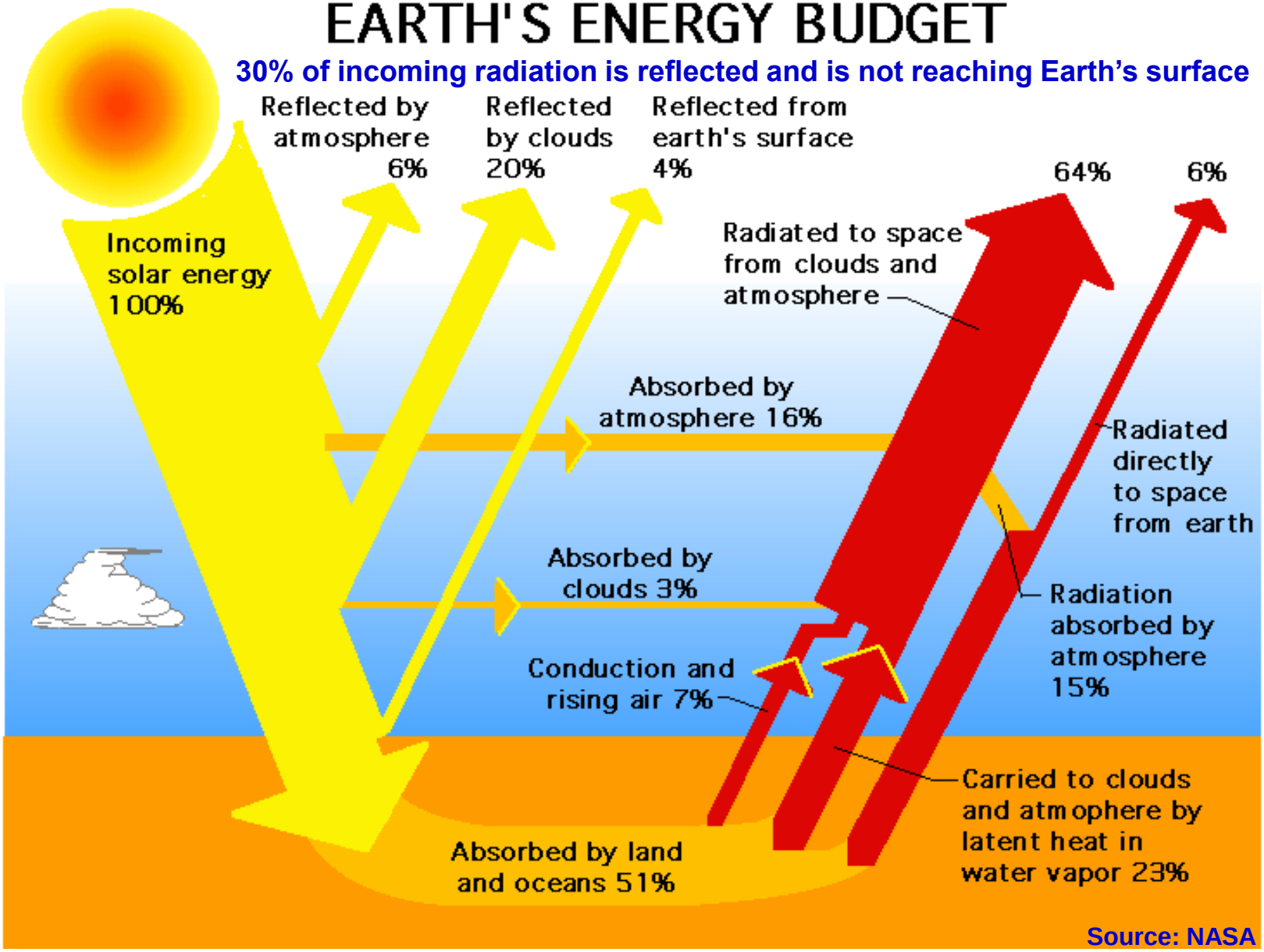
Greenhouse Effect

- Greenhouse effect occurs when a material is transparent to the incoming radiation but it absorbs the reflected infrared radiation
- This occurs in the atmosphere containing greenhouse gases



EARTH'S ENERGY BUDGET

30% of incoming radiation is reflected and is not reaching Earth's surface



Source: NASA

Radiative Equilibrium of Earth

- Planet Earth is surrounded by the near-perfect vacuum of interplanetary space
- The only significant mechanism of energy transfer between Earth and the space is through thermal radiation
- Radiative equilibrium expresses conservation of energy for such systems
- A very simple model of Earth can be formulated assuming that it is a perfect black body absorbing all solar radiation at I_S = 1366 W/m^2. Radiative equilibrium requires: $\pi R_E^2 I_S = 4\pi\sigma R_E^2 T_E^4$ $\quad T_E = \left(I_S/4\sigma\right)^{0.25} \cong 279\ \mathrm{K}$

R_E – Earth's radius; T_E – Earth's surface temperature; σ – Stefan-Boltzmann constant

Albedo

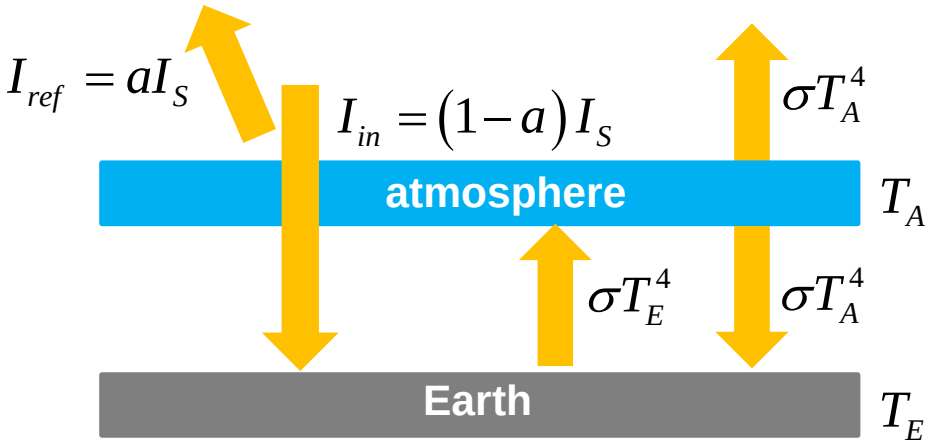
- Thus very basic radiation equilibrium consideration suggests that the Earth's temperature is about 6 °C
- The measured averaged temperature in 2017 was 14.9 °C, which is higher than our estimate
- Our simple Earth model has two main defects:
  - Not all radiation (1366 W/m^2) reaches the Earth, but only ~70%
  - Some of the Earth's radiation is reradiated back due to the greenhouse effect
- The phenomenon of reflection of fraction of incident radiation is known as **albedo**, expressed always as a number between 0 (no reflection) and 1 (complete refl.)
- Earth' albedo is equal to a = 0.3

Improved Earth Model

- When we take into consideration the albedo effect only, the Earth would be even colder. Say a=0.16, then:

$$T_E = \left[(1-a) I_S / 4\sigma \right]^{0.25} \cong 267 \text{ K} \cong -6 \ ^\circ\text{C}$$

- However, if we include the greenhouse effect, the Earth temperature increases:



Radiative equilibrium for **entire Earth and atmosphere system** gives:

$$\pi R_E^2 (1-a) I_S = 4\pi R_E^2 \sigma T_A^4 \Rightarrow T_A \cong 255 \text{ K}$$

And for **Earth's surface only** we have:

$$\pi R_E^2 (1-a) I_S + 4\pi R_E^2 \sigma T_A^4 = 4\pi R_E^2 \sigma T_E^4$$

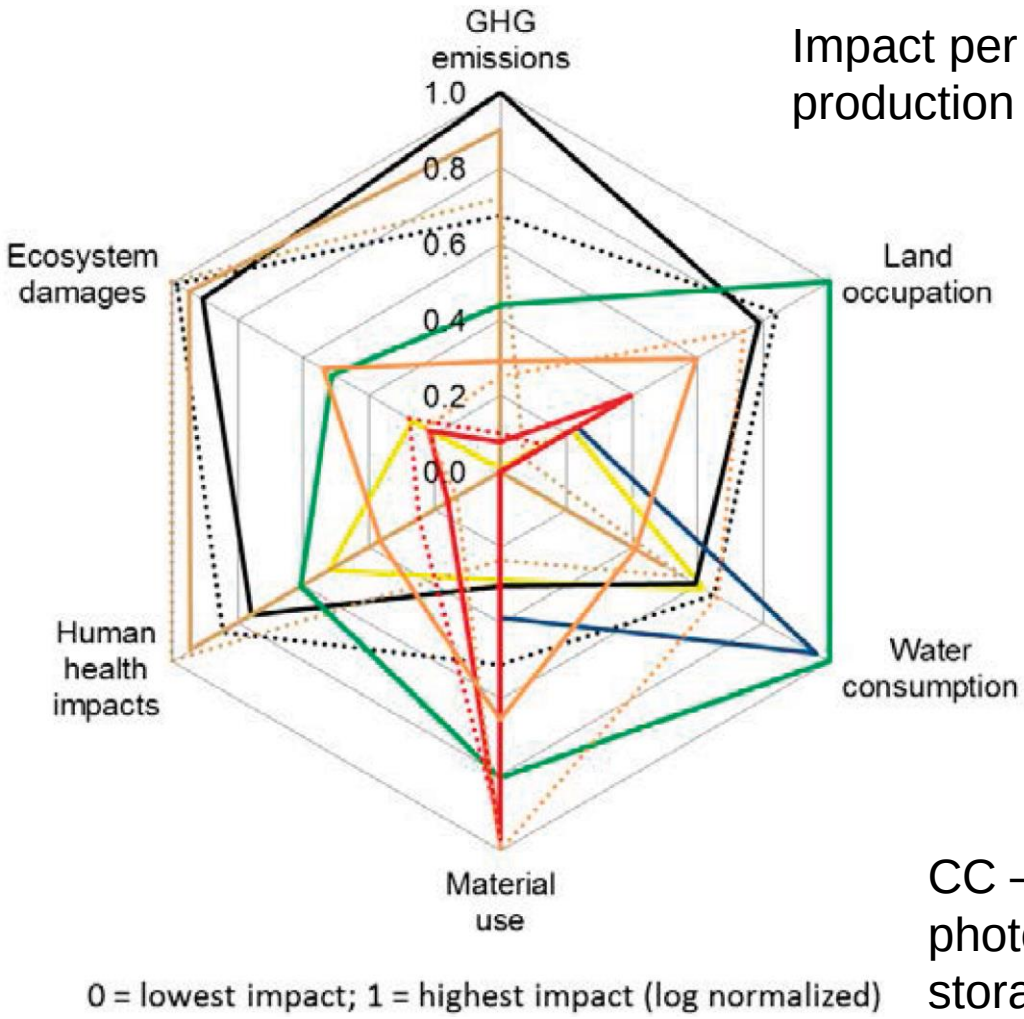
$$2T_A^4 = T_E^4 \Rightarrow T_E = \sqrt[4]{2} T_A \cong 303 \text{ K}$$

Realistic Earth Models

- Our 1-layer Earth model could predict the greenhouse effect trend, since surface temperature increase
- However, this temperature (30 °C) is too high in comparison to the measurements (14.9 °C)
- Thus a more realistic model is needed to take into account that:
  - greenhouse gases are distributed in the atmosphere and they are not perfect absorbers of all infrared radiation
  - greenhouse gases absorb certain frequencies only

- More realistic greenhouse models are based on atmospheric physics

Life-Cycle Impacts of Various ETS



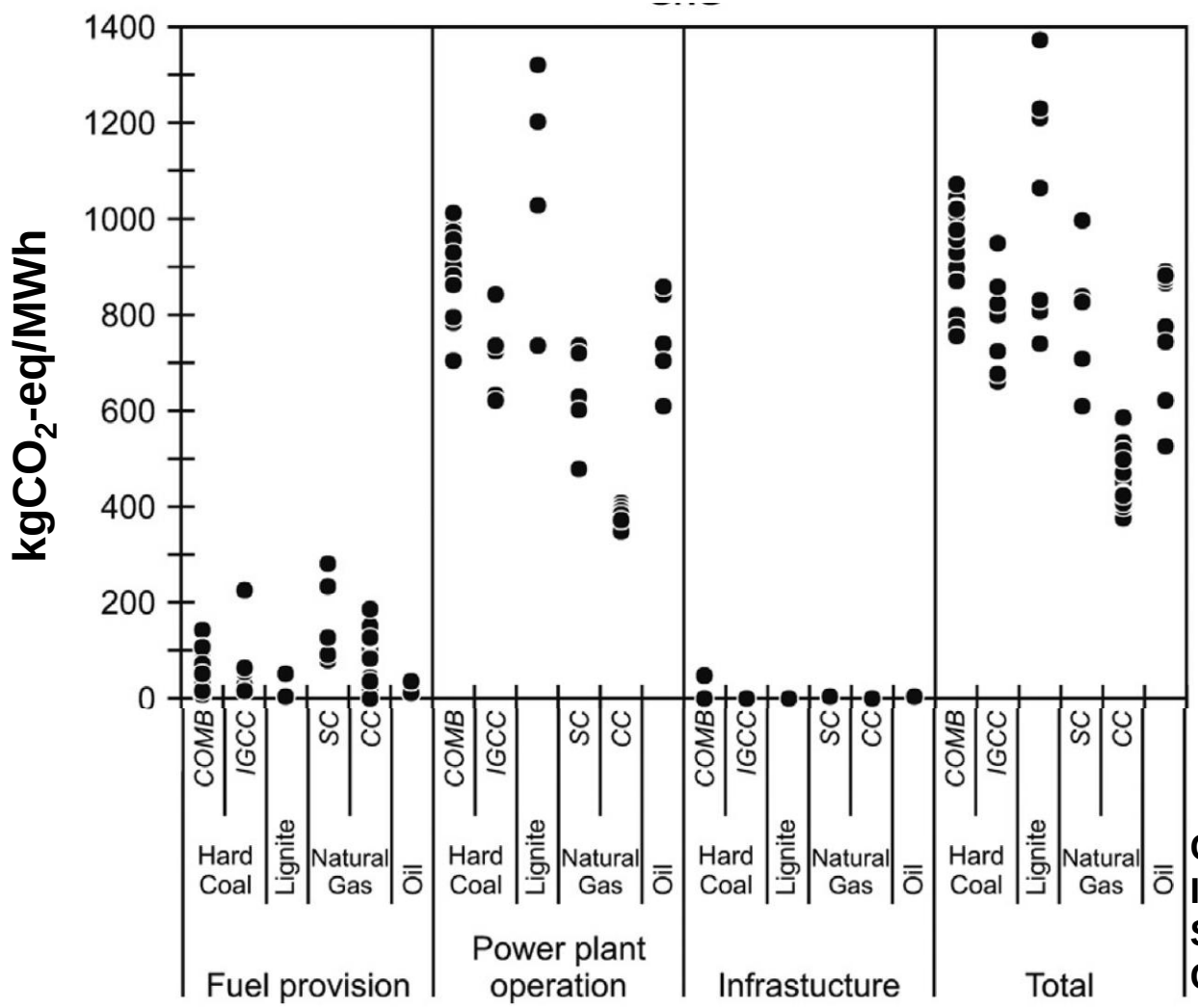
Impact per kWh for available electricity production technologies

- Nuclear
- Coal
- Coal CCS
- Gas (CC)
- Gas (CC) CCS
- Hydro
- Biomass
- Wind onshore
- Wind offshore
- Solar PV
- Solar thermal

0 = lowest impact; 1 = highest impact (log normalized)

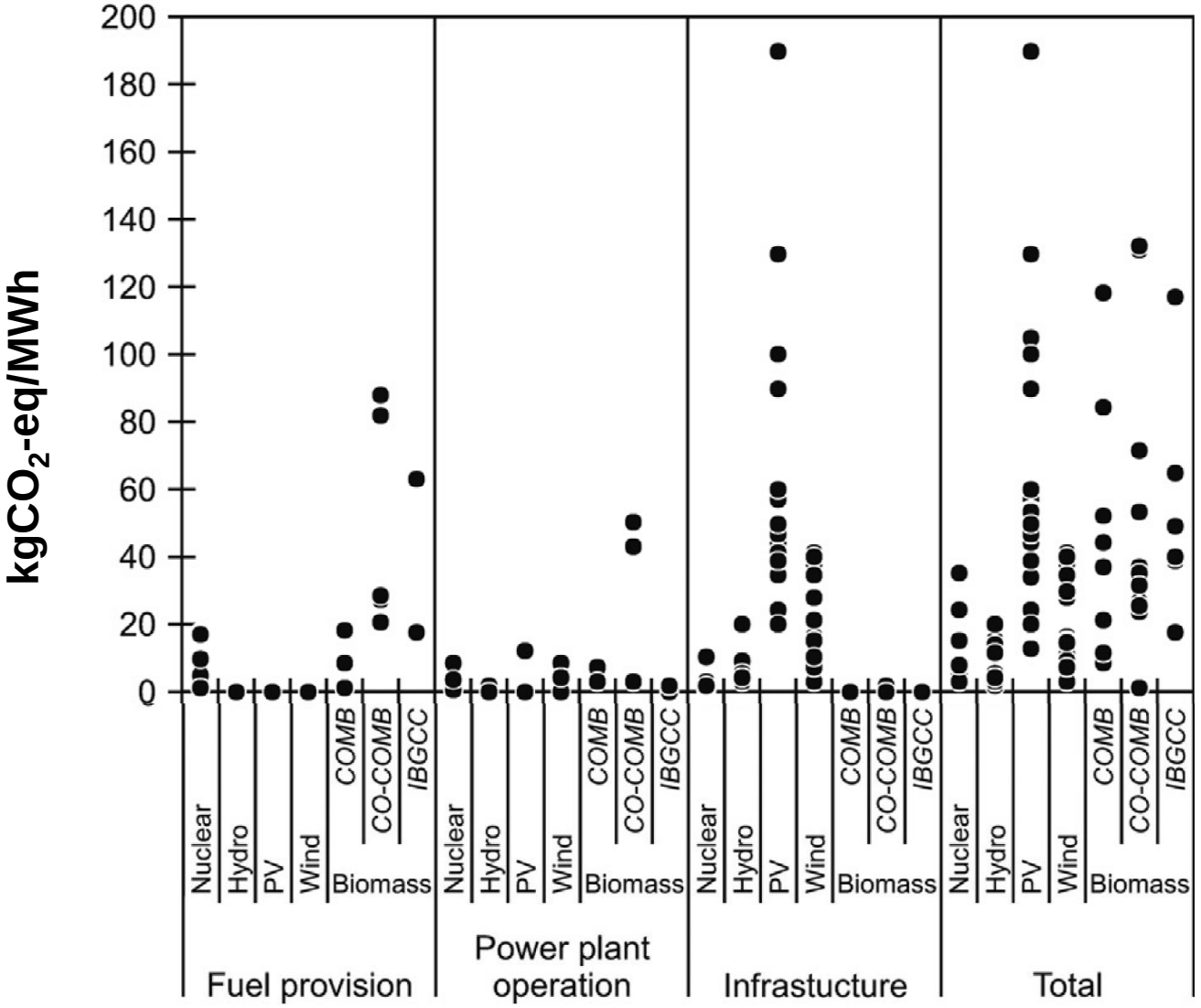
CC – combined cycle, PV – photovoltaic, CCS – carbon capture and storage, GHG – greenhouse gases

GHG Emissions from Fossil Fuels



COMB – direct combustion
IGCC – coal gasification
SC – single cycle
CC – combined cycle

GHG Emissions from Renewables&Nuclear



COMB – direct combustion
CO-COMB – co-combustion
IBGCC - gasification

Environmental Effects of Solar (1)

- Solar power plants do not produce air pollution, water pollution or greenhouse gases
- Using solar energy can have a positive effect on the environment when replacing more pollutant ETSs
- However some toxic materials and chemicals are used to make the photovoltaic cells
- Some solar thermal systems use hazardous fluids to transfer heat. Leaks of these materials could be harmful to the environment
- Large solar power plants can affect the environment near their location

Environmental Effects of Solar (2)

- Clearing land for construction and the placement of the power plant may have a long-term effect on the habitats of native plants and animals
- Some solar power plants may require water for cleaning solar collectors and concentrators or for cooling turbine generators
- Using large volumes of ground water or surface water in some arid locations may affect the ecosystems that depend on these water resources
- The beam of concentrated sunlight can kill birds and insects

Land Use by Solar (1)

- Large solar power application needs to use a few square kilometres of desert area
- Use of cultivable land is negatively affecting local environment and reducing food production

- Total land area requirements depend on the technology, the topography of the site and the solar source intensity
- Estimates for utility-scale PV system ranges from 1.4 to 4 hectares per MW, while estimates for concentrating solar thermal plants are 1.6 to 6.7 ha per MW

Land Use by Solar (2)

- Unlike wind facilities, the solar power can not share land with agriculture

- Thus use of brownfields, abandoned mining land or existing transportation corridors can reduce the negative land impact from utility scale solar

- Smaller scale solar PV arrays, that can be build on buildings, also have minimal land use impact

Water Use by Solar (1)

- Solar PV cells do not use water for generating electricity
  - however, some water is used to manufacture PV components

- Concentrating solar thermal plants (CSP) require water for cooling, depending on plant design, plant location and the type of cooling system
  - plants that employ recirculation with cooling towers withdraw about 2300-2500 litres of water per MWh of electricity produced
  - Plants with once-through cooling have higher water withdrawal but lower total water consumption (less evaporation)

Water Use by Solar (2)

- Dry-cooling technology can reduce water use by about 90%
  - however, the cost of this solution is higher and the efficiency is lower
  - This solution is significantly less effective at temperature above 37 °C

- Many regions with highest potential for solar energy also tend to be those with driest climate
  - thus careful consideration of water usage tradeoffs is essential

Hazardous Materials (1)

- The PV cell manufacturing process includes a number of hazardous materials mainly used to clean and purify the semiconductor surface
  - this chemicals include hydrochloric acid, sulfuric acid, hydrogen fluoride and acetone.
  - the amount used depends on the type of cell, the amount of cleaning that is needed and the size of silicon wafer
  - workers face risk associated with inhaling silicon dust

- Thin-film PV cells contain a number of more toxic materials: gallium arsenid, copper-indium-gallium-diselenide, cadmium-telluride, etc.

Hazardous Materials (2)

- If these materials are not handled and disposed of properly, they could pose serious environmental or public health threats

- Since, however, they are quite expensive and rare, manufactures have strong incentive to ensure that these materials are recycled.

Global Warming Emissions by Solar

- There are no global warming emissions associated with generating electricity from solar energy
- There are life-cycle emissions associated with manufacturing, material transportation, installation, maintenance, decommissioning and dismantlement
- Most estimates of life-cycle emissions for photovoltaic systems are between 32 and 82 grams of CO_2 equivalent per kWh.
- For CSP the estimates are 36-91 gCO_2/kWh

Fossil Technologies (1)

- Fossil technologies perform poorly in terms of
  - greenhouse gas emissions
  - bad impact on ecosystems, human health
  - land use (coal mining)

- Ecosystem damages result from
  - acidification due to deposition of acid chemicals
    - leads to the impairment of fishwater, soils, forests and vegetation
  - eutrophication caused by pollutants from mining, power plant waste treatment and emission from combustion
    - leads to excessive algal growth and severe impairment to water quality

Fossil Technologies (2)

- Health impacts arise largely from toxic releases such as
  - metal leaching from coal mines
  - particulate emissions from combustion

- Carbon capture and sequestration can reduce GHG emissions, but it tends to worsen performance across all other categories due to
  - overall reduced efficiency
  - use of toxic material for capture

Coal Power Plant Emissions

- Environmental impact from coal plants is substantial
  - portion of ash remains in the combustion chamber (bottom ash)
  - fly ash leaves the combustion chamber with the flue gases
- The fly ash can contain toxic trace elements:
  - lead, cadmium, arsenic
- The flu gases contain:
  - carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen oxides (NO_x)
  - substantial amount of mercury
- Electrostatic precipitators used to remove particles

Sulphur Dioxide

- Sulphur dioxide causes respiratory problems, and lead to acid rain and smog
- A number of mechanisms are used to remove sulphur
  - application of alkali material like limestone to absorb SO_2
  - scrubbing of flue gases with limestone produces calcium sulphite ($CaSO_3$) which can be removed and further oxidized to form gypsum (a commodity valuable in the building industry)

Nitrogen Oxides

- Nitrogen oxides
  - (predominantly NO and NO_2 from coal combustion, but also including N_2O, N_2O_2, collectively denoted NO_x
  - form by oxidation of nitrogen by combustion air at temperatures of 1300 °C and above
  - they lead to ozone production in the lower atmosphere, which is the major component of smog
- Usage of FBC (fluidized bed combustion) lowers the combustion temperature and reduces NOx production
- NOx can be also removed by selective catalytic reduction (ammonia is mixed with the flue gas and passed through a catalyst to react NO_x with NH_3 -> N_2 + H_2O)

Mercury

- Mercury-containing compounds are present in flue gases from coal combustion
- Mercury can cause neurological problems in people and animals
- Mercury can be removed from emissions by mixing an absorbent powder into the flue gases
- The powder reacts with the mercury to form particles that can be removed by the electrostatic precipitator system

Biomass Technology

- Biomass technology performs poorly across most impact categories
  - particularly in land and water use
  - biomass production allows around 5 tonnes per hectare and year
  - typical energy density of biomass is 12 MJ/kg
  - this gives energy production rate of 60 GJ/ha y
  - to supply 40 EJ/y would require 7×10^6 km^2 (20% of all forested land on Earth)

Hydropower

- Hydropower performs well for all categories with the exception of water consumption

- However, this effect is highly site dependent

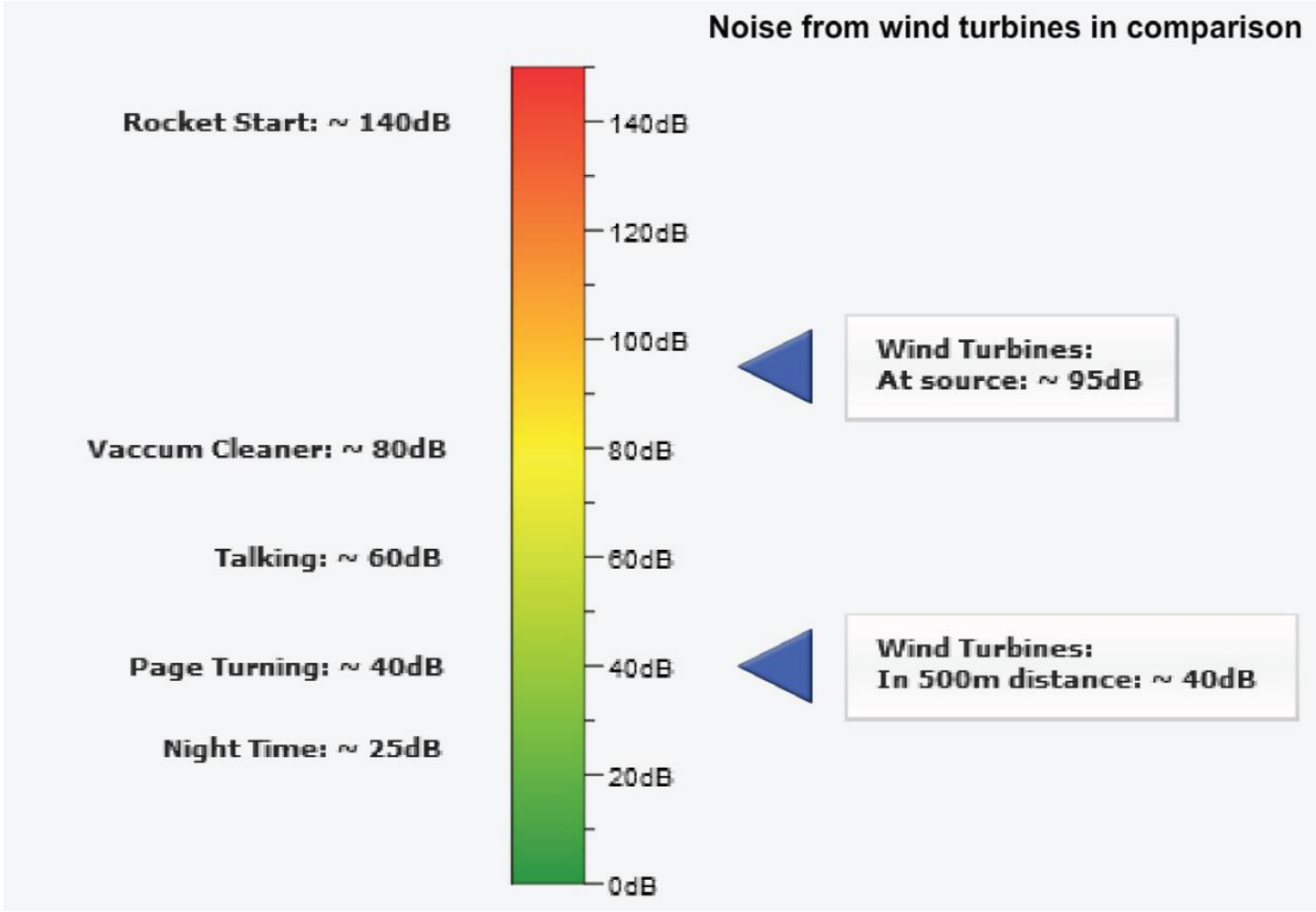
Variable Renewable

- In general variable renewable (solar, wind) perform well
- Exception is the use of construction materials, such as cement and metals (aluminium, copper, iron) and relatively high land requirements for solar technologies
- Wind power has the highest material use among all technologies

Wind Energy and Environment

- The areas of concern for wind power include
  - noise affecting nearby resident
  - shadow flicker irritating for human eys
  - visual impact on the landscape
  - bird collisions
- Sources of noise
  - aerodynamic noises – motion of blades causing turbulencies when passing the tower
  - shaft and bearings noise
  - gearbox noise

Noise from Wind Turbines



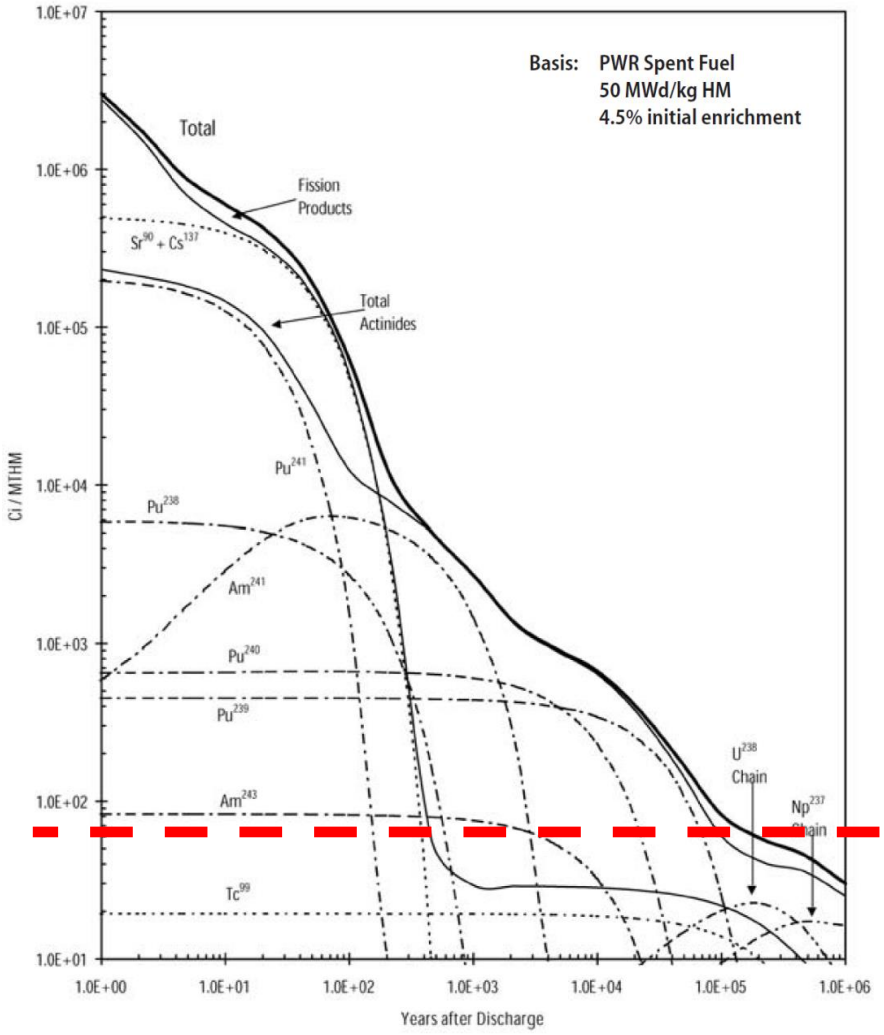
Nuclear

- Nuclear has among the lowest impact
- Exception is the water consumption, which is similar to other thermal generation technologies
  - this conclusion is based on water consumption for plants with evaporative cooling towers (not always the case)
- Health impacts are above those of some renewables
  - due to radiation in mining and fuel reprocessing

Nuclear Issues

- Nuclear power faces several environment-related issues such as
  - potential for release of significant amounts of radioactive materials (occurred in Chernobyl)
  - potential for proliferation of nuclear weapons
  - disposal of high-level wastes
- Public acceptance for nuclear very much depends on how these issues are resolved

Spent Fuel Radioactivity



Level of natural uranium achieved after ~150000 y