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Lecture 2:

Climate change and Challenges

Greenhouse effect

- Since the Industrial Revolution there has been a sharp increase in the burning of fossil fuel and the consequent release of CO_2 , a **greenhouse gas**. The main greenhouse gases in the atmosphere are water vapour (and water droplets) and CO_2. These gases absorb infrared radiation, which affects the temperature of the Earth.

- **Without an atmosphere**, the Sun's radiation would impinge directly on the Earth's surface and would heat the surface up to around **−1 °C**, at which temperature it would radiate energy back out into space at the same rate as received from the Sun.

- The atmosphere radiates some infrared radiation back to the Earth's surface, which thereby receives more radiant energy than with a completely transparent atmosphere. The surface temperature rises until the Earth's surface emits energy at the same rate as it receives energy, and is known as the **greenhouse effect**.

Surface temperature without greenhouse effect

First suppose that Earth's atmosphere does not absorb incident solar radiation nor radiation emitted by Earth's surface.

Then for energy equilibrium, the rate of energy incident on the Earth's cross-section πR^2 equals the rate at which energy is radiated back into space from the whole area $4\pi R^2$.

Hence $$(1-A)S\pi R^2 = 4\pi R^2 \varepsilon\sigma T^4$$

Assuming $\varepsilon = 1,\ A = 0.1,\ S = 1.372\,\text{kWm}^{-2},\ \sigma = 5.67\times10^{-8}\,\text{Wm}^2\text{K}^{-4}$
gives $T = 272\,\text{K} = -1^{\circ}\text{C}$.

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Greenhouse effect

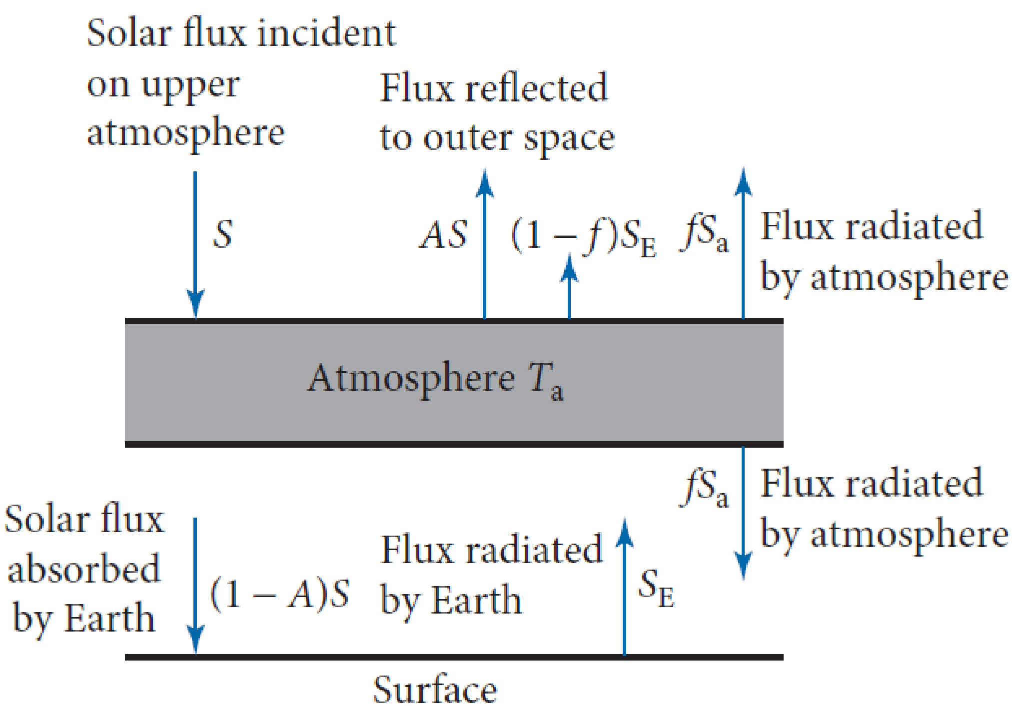


Fig. 2.2 Greenhouse effect.

Putting A = 0.3, f = 0.77 gives

T_E = 288 K = 15 °C

For energy equilibrium of the atmosphere,

$$f\,S_a\,4\pi R^2 + (1-f)S_E\,4\pi R^2 + AS\pi R^2 = S\pi R^2$$

For energy equilibrium of the Earth's surface,

$$S_E\,4\pi R^2 = (1-A)S\pi R^2 + f\,S_a\,4\pi R^2$$

Adding gives,

$$(2-f)S_E\,4\pi R^2 = 2(1-A)S\pi R^2$$

Assuming $\varepsilon = 1$, $S_E = \sigma T^4$, then

$$T_E^4 = \frac{(1-A)S}{2(2-f)\sigma}$$

Global warming

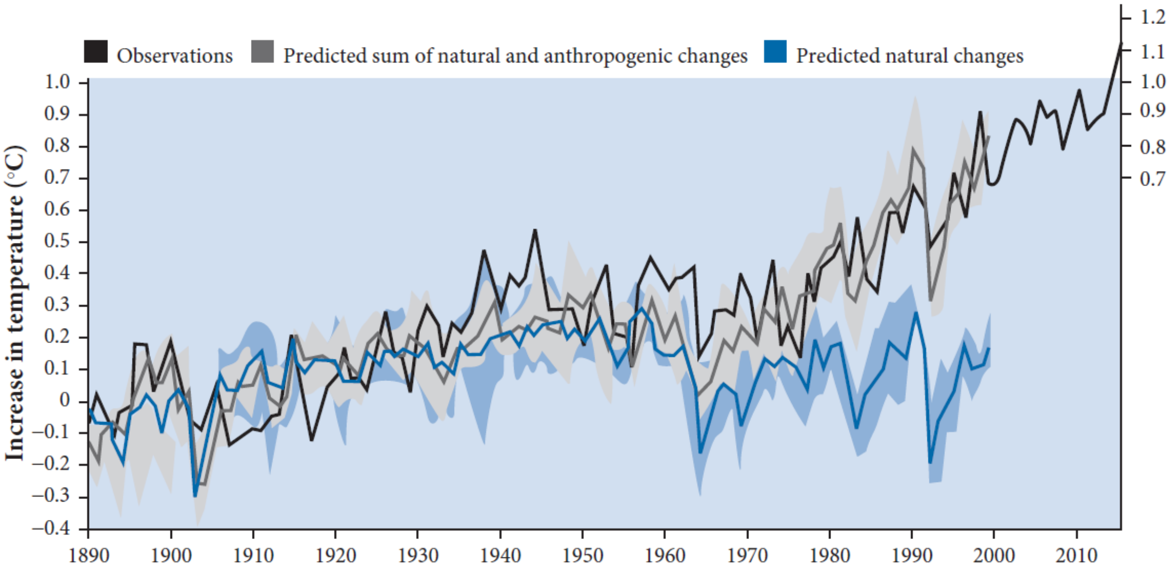


Fig. 1.10 Curves showing global temperatures 1890–2015. Measured; predicted with only natural changes; and predicted with natural plus anthropogenic changes 1890–2000.

(a) Polar bear habitat ©Howard Perry/istock
(b)Flooding in Asia: 1000 Words/shutterstock

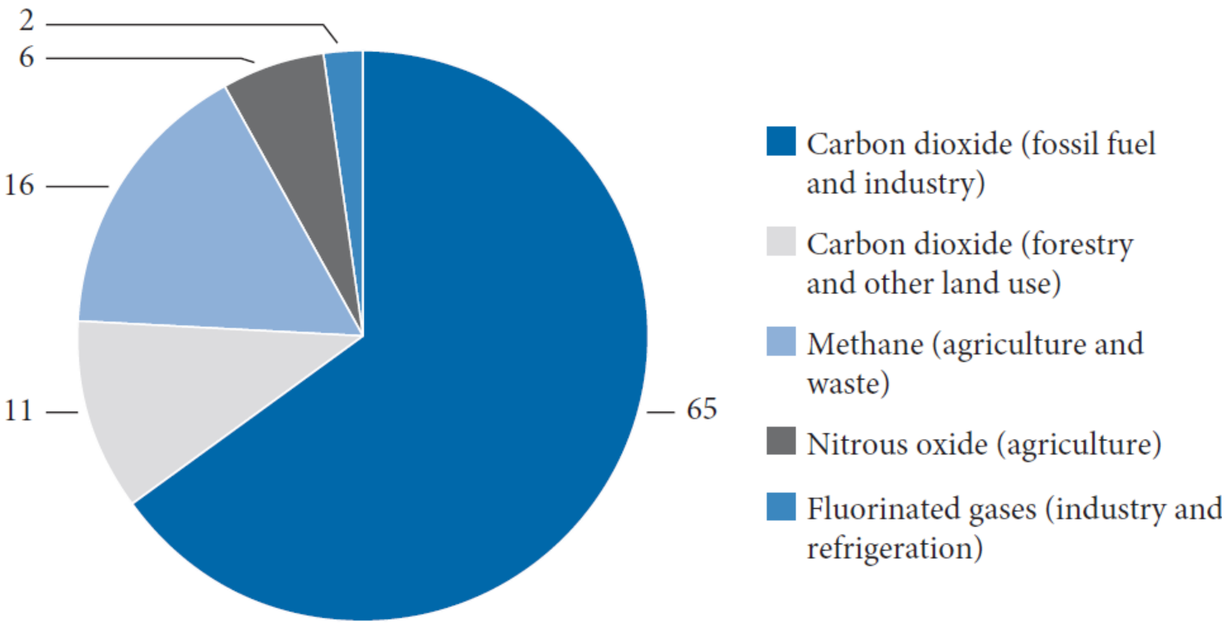
- The greenhouse effect causes a temperature rise of about **15 °C**.
- Over the twentieth century, the average global temperature rose by **0.6 ± 0.2 °C**
- IPPC (ar5) says: ‘Since the 1950s… the atmosphere and ocean have warmed, the amounts of snow and ice have diminished and sea level has risen.’

The **Arctic Ocean is also now projected to be ice-free during the summer** under a high emissions scenario by mid-century.

The effect of doing nothing (Business As Usual)

- IPPC (ar5) says that by the end of the twenty-first century, if the world continued to produce energy mainly from fossil fuels – the **business-as-usual (BAU) scenario** - the temperature rise by 2100 relative to the average from year 1850-1900 is about as likely as not to exceed 4 ^{o}C.
- Such a temperature rise would put the world at considerable risk of significant climate change, with a major impact on life on earth.
- Although this would be only a relatively small change in the global mean temperature, it would increase the chance of extreme weather conditions considerably
- IPPC (ar5) says ‘It is very likely that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise’.

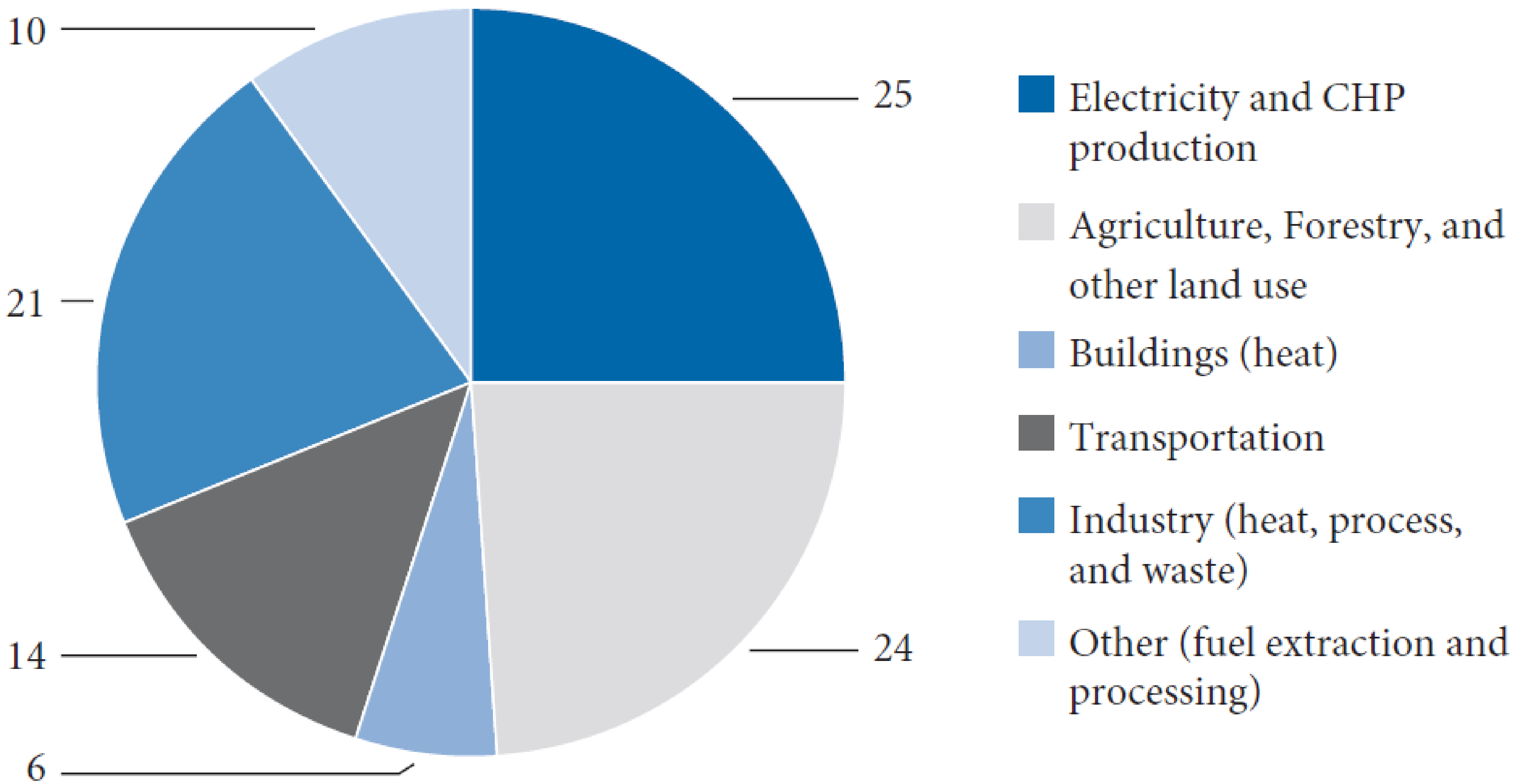
Greenhouse gases



- Main greenhouse gas is water vapour (and water droplets). CO_2 concentration has risen from 280 ppm in 1750 to 405 ppm in 2015.

- Timescale for excess of water vapour in the atmosphere to disappear is a few days but, for other greenhouse gases and the response of interactions between the oceans and atmosphere, it is typically 10–1000 years!
- Aerosols tend to have a cooling effect on the climate and cancel out the warming effect of the non-CO_2 greenhouse gases such as methane. The net result is that the level of CO_2 equivalent gases (CO_2eq) is close to that of CO_2 alone.

Major producers of greenhouse gases



Capacity or load factor

Capacity factor = (annual energy output)/(energy output at rated power)

Power density = average electrical power output per km^2

Table 1.2 Capacity factor, power density, LCA, and LCOE of some fossil and low-carbon sources (OpenEI, Lazard)

Source	Capacity factor (%)	Power density (MWe per km^2)	Life-cycle analysis (gCO_2 per kWh)	Levelized cost ($cents per kWh)
Coal	~60	~1000	979	7–15
Gas (CCGT)	~50	~1000	477	5–8
Nuclear	~90	~1000	12	10–14
Solar PV	~10–25	~5–10	44	4–7
Wind onshore	~20–40	~2	11	3–8

Renewable farm lifetime 30 years, interest rate 6%, M&O 4% of capital per year
LCOE ≈ 1.3 $C_{capital}$(k$ per kW)/capacity factor

Power requirement and density

- For good HDI need ~ 2 toe y^{-1} per person final energy, equivalent to ~ 65 kWh d^{-1} or ~ 2.7 kWe continuous per person

- India 1.33 billion, area 3.3 million km^2

  China 1.38 billion, 9.6 million km^2

  USA 0.32 billion and 9.9 million km^2

  Africa 1.22 billion and 30 million km^2

- Parts have good solar intensity so ~10 MWe km^{-2} possible, so percentage of land area required is about 10%, 4%, 1%, and 1%.

The global challenge

- To provide the energy different countries need to improve their standard of living while drastically reducing their dependence on fossil fuels.
- To increase very significantly the energy supply from renewables.
- To address the interrelated demands of water, food, and energy.
- To reduce the cost of renewable energy to below that of fossil fuels.

The global challenge

- To decarbonize heat, as well as electricity generation.
- To achieve the reduction in GHG emissions, need to reduce global demand for energy by improving end-use efficiency and by energy savings
- Important that the emissions (carbon footprint) associated with all activities are reduced.
- Need to strengthen international efforts. The Paris Agreement in 2015 was encouraging but the proposed national contributions have been estimated to limit global warming to only 2.7 ^{o}C

Key units

Quantity	Unit	Definition
Force	newton (N)	Force required to accelerate 1 kg by 1 m s^{-2}
	pound-force (lbf)	Weight of 1 pound ≈ 4.45 N
Energy	joule (J)	Work done by force of 1N in moving 1 kg by 1 m
	kilowatt-hour (kWh)	$10^3 \times 60 \times 60 = 3.6 \times 10^6$ joules = 3.6 MJ ≈ 3412 Btu
	EJ	10^{18} joules ≈ 278 TWh ≈ 23.9 Mtoe
	calorie	Energy to heat 1 g of water by 1 °C ≈ 4.2 J
	Btu	Energy to heat 1 lb of water by 1 °F ≈ 1.055 kJ
Power	watt ($W = J\ s^{-1}$)	1 joule per second = 1 volt-ampere
	horsepower	550 ft lb per second ≈ 0.746 kW
Fuel equivalence	tonne oil equivalent (toe)	41.868 GJ = 11.63 MWh ≈ 1.5 tonne hard coal
	barrel oil equivalent (boe)	42 US gallon ≈ 159 litres of oil ≈ 6 GJ

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Dimensional analysis

Derive an algebraic formula for the potential energy per unit wavelength per unit width of wave-front V of a surface water wave in terms of the density ρ, amplitude a, and acceleration due to gravity g.

Assume an algebraic expression of the form $V = k\rho^{\alpha} a^{\beta} g^{\gamma}$, where k is a dimensionless constant.

$$\frac{[\text{potential energy}]}{[\text{wavelength}]\times[\text{width}]} = \frac{[\text{force}]\times[\text{distance}]}{[\text{length}]^2} = \frac{\mathrm{ML^2T^{-2}}}{\mathrm{L^2}} = \mathrm{MT^{-2}}$$

so

$$\mathrm{MT^{-2}} = (\mathrm{ML^{-3}})^{\alpha}\,\mathrm{L}^{\beta}(\mathrm{LT^{-2}})^{\gamma} = \mathrm{M}^{\alpha}\mathrm{L}^{-3\alpha+\beta+\gamma}\mathrm{T}^{-2\gamma}$$

Equating indices, we have $\alpha = 1$, $-3\alpha + \beta + \gamma = 0$, $-2\gamma = -2$, yielding $\alpha = 1$, $\beta = 2$, $\gamma = 1$. Hence, $V = k\rho a^2 g$. To derive the form of k it is necessary to have some knowledge of fluid mechanics

Key points

- Global energy production is expected to increase by around a third between 2014 and 2035, with most of the increase being in the developing countries.
- The greenhouse effect is a natural phenomenon due to absorption of solar radiation by the Earth's atmosphere, raising the temperature on the surface of Earth by about 15 °C.
- The main greenhouse gas is water vapour. Carbon dioxide, methane, CFCs, and other greenhouse gases enhance the effect of water vapour by increasing its amount.
- The characteristic timescale for an excess of water vapour in the atmosphere to disappear is a few days, but, for other greenhouse gases and for the response of the interactions between the oceans and atmosphere, the characteristic timescales are typically 10–1000 years.

Key points

- Carbon dioxide concentrations have risen from about 280 parts per million by volume in 1750 to about 405 parts per million by volume today (2017).
- Carbon dioxide emissions need to fall to zero by ~2100 in order to limit the atmospheric concentration to ~450 ppmv and to restrict the temperature rise, global warming (compared to pre-industrial times) to 2 °C.
- Continuing to rely predominantly on fossil fuels for our energy—the business-as-usual scenario—could cause a temperature rise of ~4 °C and put the world at risk of significant climate change.
- Decarbonizing our electricity and energy (which includes heat) supply, coupled with energy savings, is essential in order to combat climate change.
- The cost, power density, and availability of low-carbon sources are particularly important, and the handling of variable supplies through energy storage, interconnectors, and demand management will become increasingly necessary.