Sustainable energy

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1. Motivations

Typical quotes about energy:

- There is an impending energy crisis. We are running out of oil! Even nuclear power cannot save us because in less than twenty years, uranium reserves will be depleted.

- Nuclear power is the solution for solving the energy crisis.

- We have a huge amount of wind and sun.

- Los Angeles residents drive a total of 142 million miles - the distance from Earth to Mars - every single day.

- Switching off your computer before going to bed could reduce CO_2 emissions by 5 million tons every year.

There is a lack of meaningful facts and numbers when dealing with energy policy. And even when they are numbers, they are meant to impress, not to inform

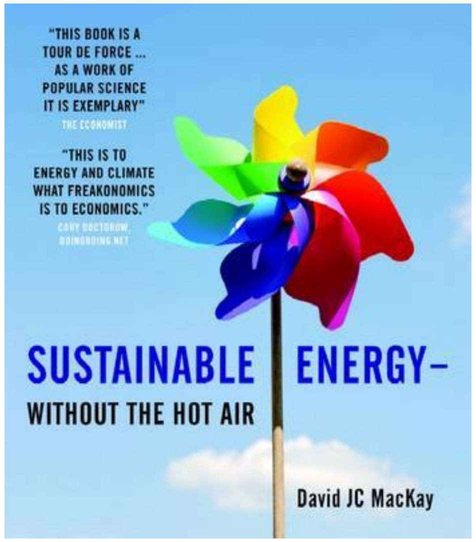
Main objective of the class: to learn to deal with numbers which are comprehensible, comparable and easy to remember so as to be better placed to answer questions such as:

1. Can countries such as Belgium, France, the UK or the USA conceivably survive on their own renewable energy sources?

2. If everyone turns their thermostats one degree closer to the outside temperature, drives a smaller car, and switches off their phone chargers when not in use, will an energy crisis be averted?

3. Is the population of the Earth six times too big?

Main organisational aspects of the class

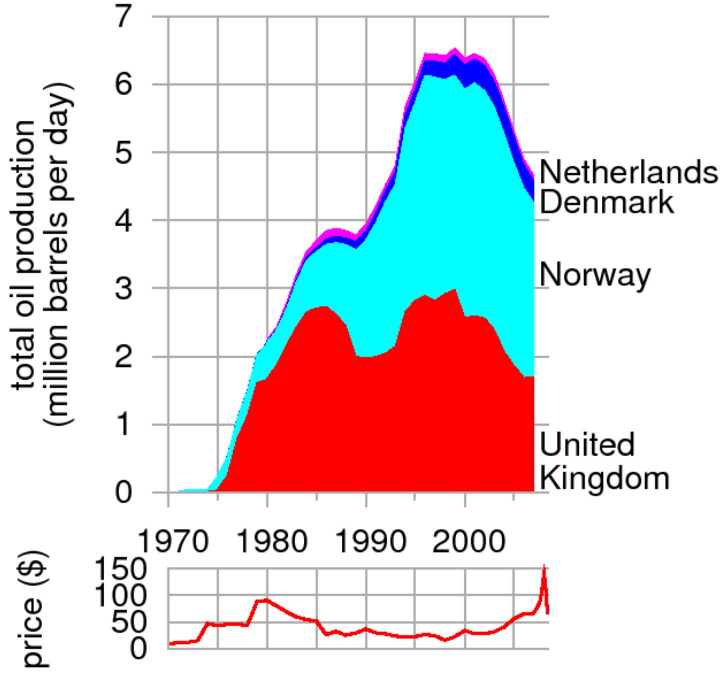


- Plenary lectures based on the book "Sustainable energy - without the hot air" from David JC MacKay. Teacher: Damien ERNST
- Plenary lectures given by invited guests.
- Group sessions where you will have to make presentations in English!

Detailed information on my website : http://www.damien-ernst.be

Why are we discussing energy policy?

1. Fossil fuels are a finite resource (we will run out of cheap gas and oil in our lifetime) that should be used for better uses than simply setting fire to them.
2. Even if fossil fuels are still available around the world, we perhaps do not want to depend on untrustworthy foreigners.
3. The climate change motivation: the burning of fossil-fuel is a major contributor to climate change through the release of carbon dioxide emissions (CO_2).



The climate change motivation

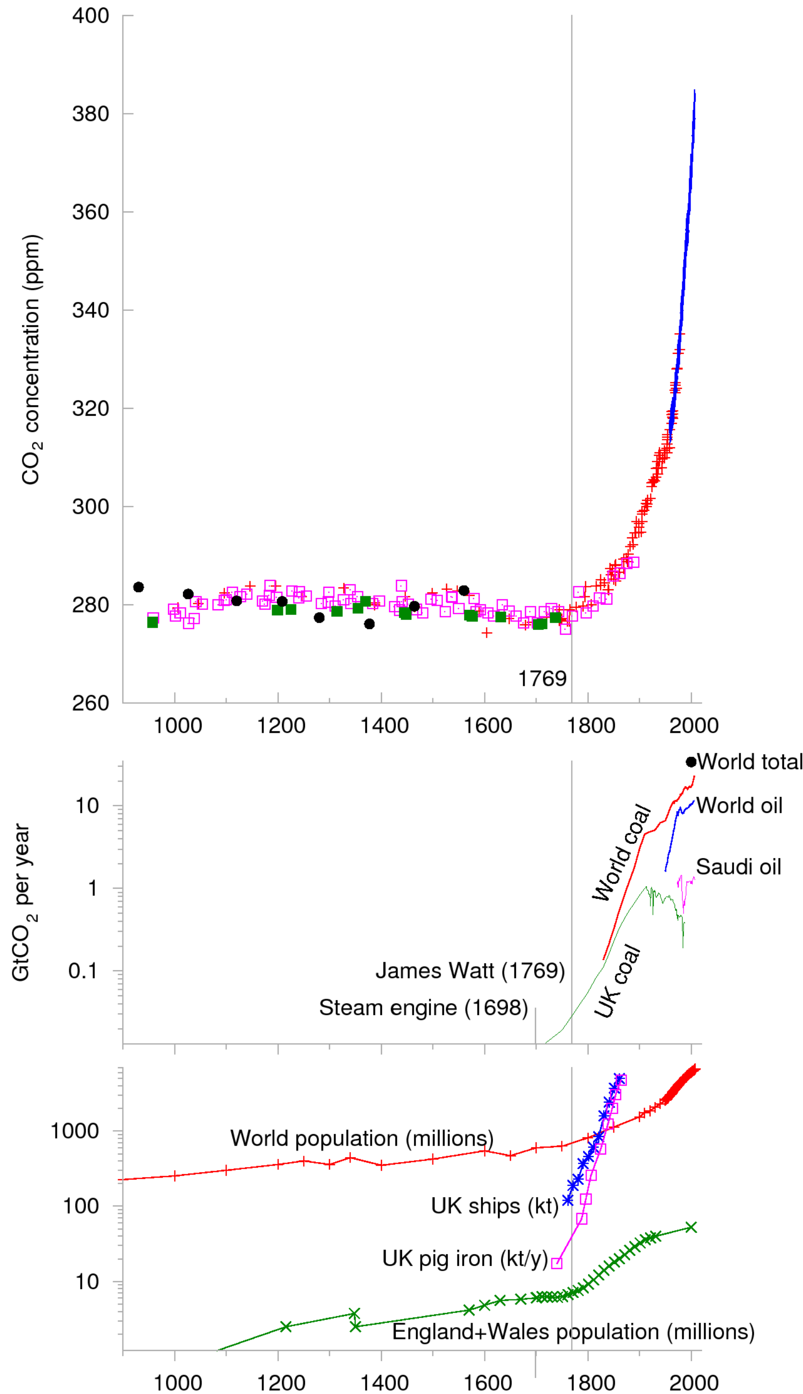
Argued in three steps:

1. The burning of fossil fuels by humans causes carbon dioxide concentrations to rise.

2. Carbon dioxide is a greenhouse gas.

3. Increasing the greenhouse effect changes the climate (e.g., an increase in average global temperatures).

Step 1: Burning fossil fuel ⇒ increase in CO_2 concentration



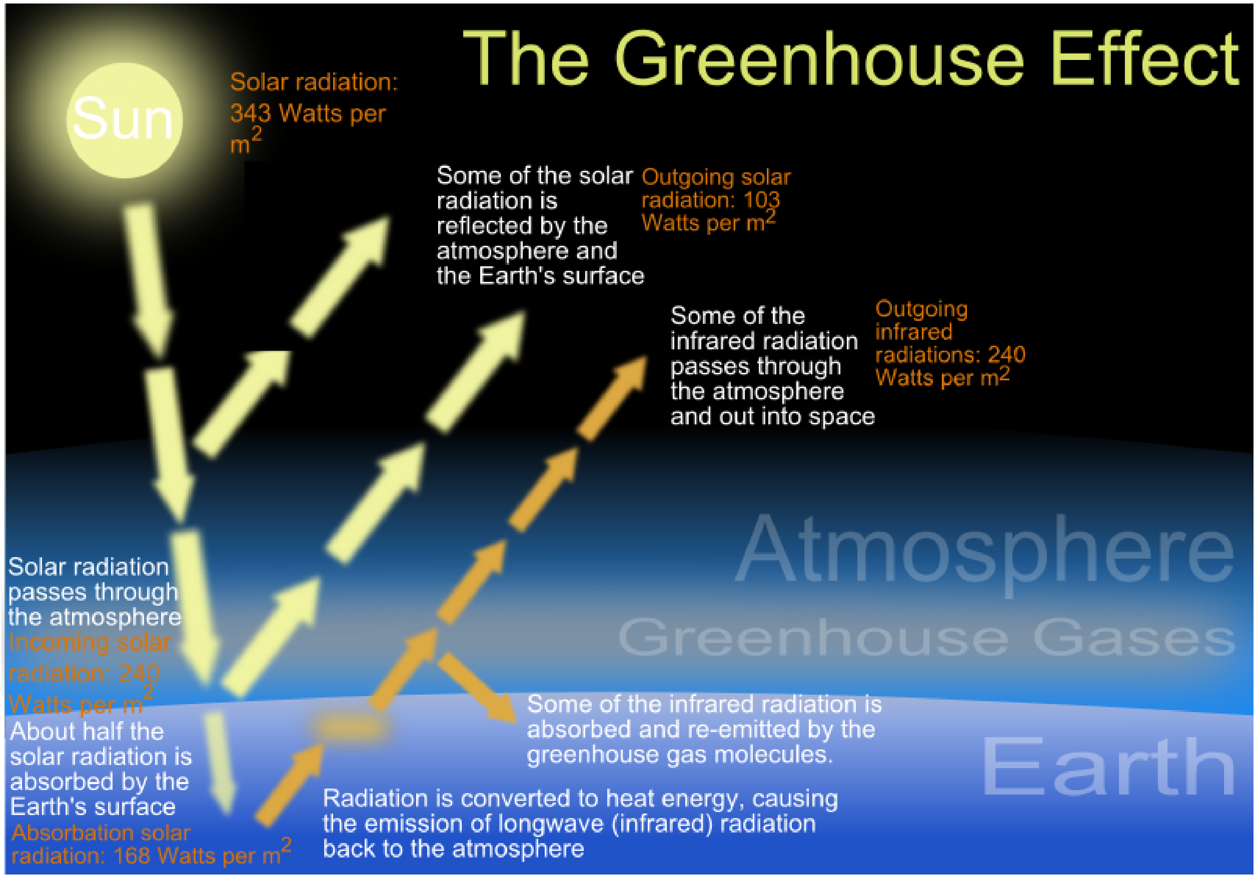
The graphics are convincing but climate change negationists will say:

The burning of fossil fuels sends about 24 gigatons of $C0_2$ per year into the atmosphere, which may sound a lot. Yet the biosphere and the oceans send about 440 gigatons and 330 gigatons of CO_2 in the atmosphere per year, respectively. So the blame cannot be put on human fuel-burning for this increase in CO_2 concentration.

What you should answer them:

The burning of fossil fuels has disrupted the natural balance that existed between CO_2 flows *into* the atmosphere with large natural flows *out* of the atmosphere back into the biosphere and the ocean. It is this disruption of balance that causes CO_2 concentrations to rise.

Step 2: CO_2 is a greenhouse gas



Obvious since it can be shown (through experiments) that CO_2 absorbs and emits radiation within the thermal infrared range.

A few facts about greenhouse gases

Water vapor (H_20) contributes to 36-72% of the overall greenhouse effect, followed by CO_2 (9-26%), CH_4 (4-9%) and O_3 (3-7%).

Non-greenhouse gases such as CO may have an indirect radiative effect by elevating the concentration of greenhouse gases.

The atmospheric lifetime of CO_2 is estimated of the order of 30-95 years.

The Global Warming Potential (GWP) of a gas depends on both its efficiency as a greenhouse gas and its atmospheric lifetime. Measure relative to the same mass of CO_2 released at the same time.

Examples of GWP for specific timescales:

Gas name	Chemical formula	Lifetime (years)	20-yr	100-yr	500-yr
Carbon dioxide	CO_2	30-95	1	1	1
Methane	CH_4	12	72	25	7.6
Nitrous oxide	N_2O	114	289	298	153
CFC-12	CCl_2F_2	100	11 000	10 900	5 200
HCFC-22	$CHClF_2$	12	5 160	1 810	549
Tetrafluoromethane	CF_4	50 000	5 210	7 390	11 200
Hexafluoroethane	C_2F_6	10 000	8 630	12 200	18 200
Sulphur hexafluoride	SF_6	3 200	16 300	22 800	32 600
Nitrogen trifluoride	NF_3	740	12 300	17 200	20 700

[Taken from en.wikipedia.orgwikiGreenhouse_gas]

Step 3: Increasing greenhouse effects leads to climate change

Here, there is a lot of uncertainy! Climate science is difficult. For example, we cannot be certain how much warmer the Earth would be if the amount of CO_2 were to double.

Consensus on the best climate models: doubling CO_2 concentration would have roughly the same effect as increasing the intensity of the sun of 2% and would bump up the temperature by approximately 3 °C.

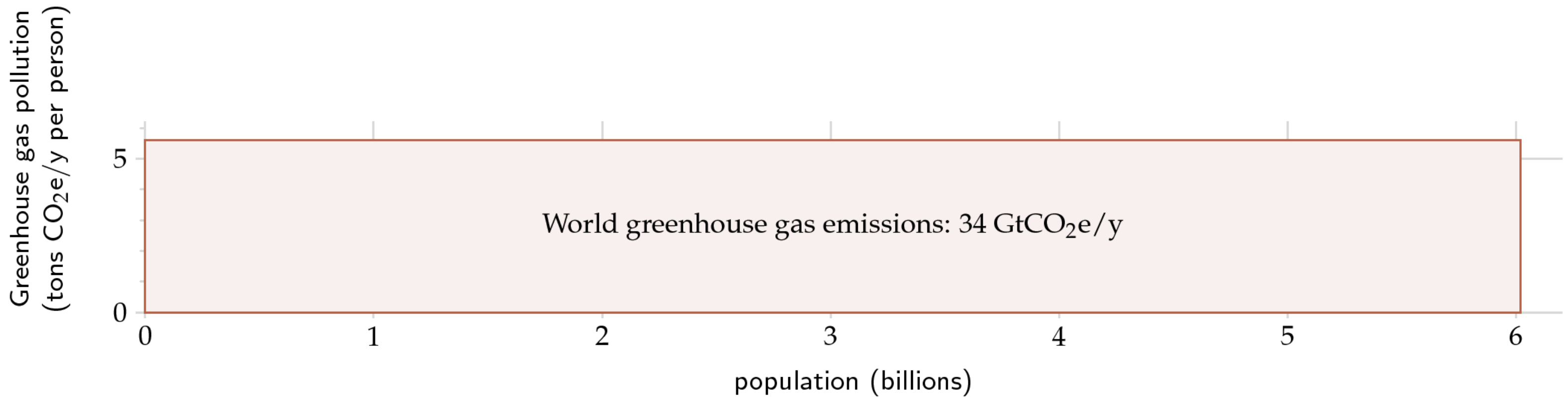
And you know the litany: the Greenland icecap will gradually melt, sea-level will rise, ecosystems will be significantly altered, droughts, hurricanes, etc.

How to compute who is responsible for climate change?

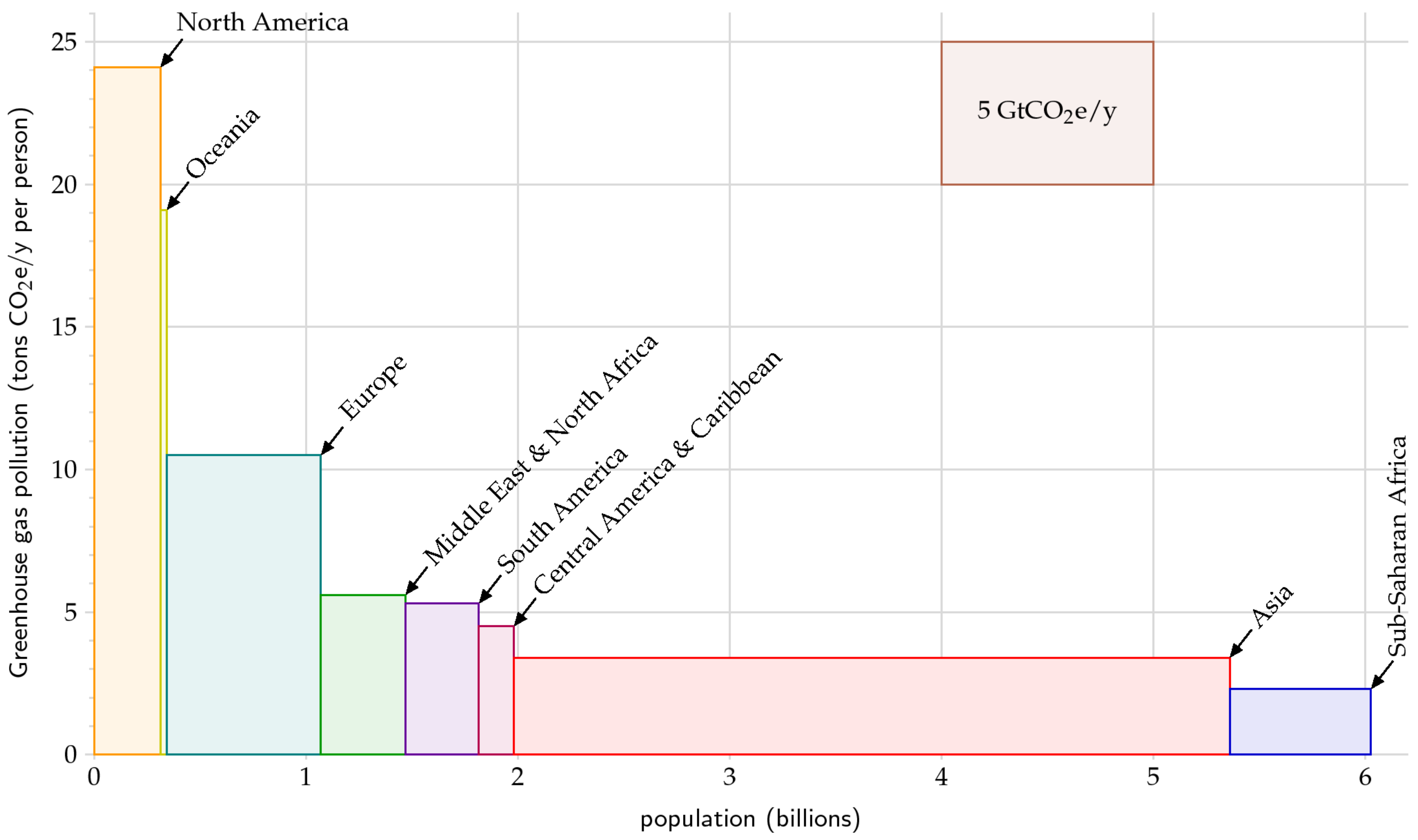
Three main greenhouse gases exist (carbon dioxide, methane, and nitrous oxide) with different physical properties. It is conventional to express all gas emissions in "equivalent amounts of carbon dioxide". "Equivalent" means "having the same warming effect over a period of 100 years".

Units: One ton of carbon-dioxide-equivalent ($1tCO_2e$) or one billion tons of carbon-dioxide-equivalent ($1GtCO_2e$.)

The world's greenhouse gas emission in 2000: 34 billion tCO_2e or about 5,5 tons CO_2e per year per person.

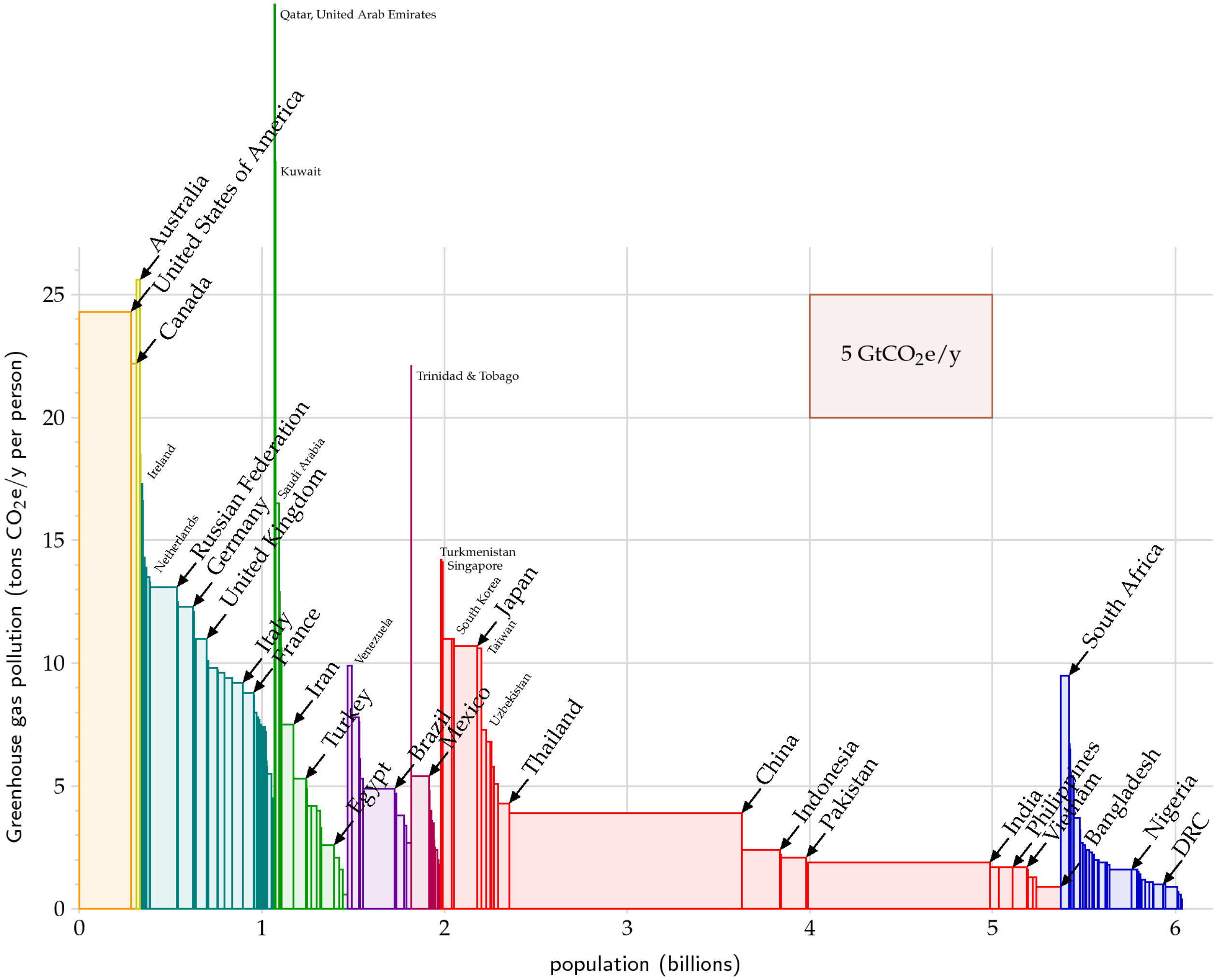


Responsibility by region



Observation: North America per captica emission is 4 times the world average!

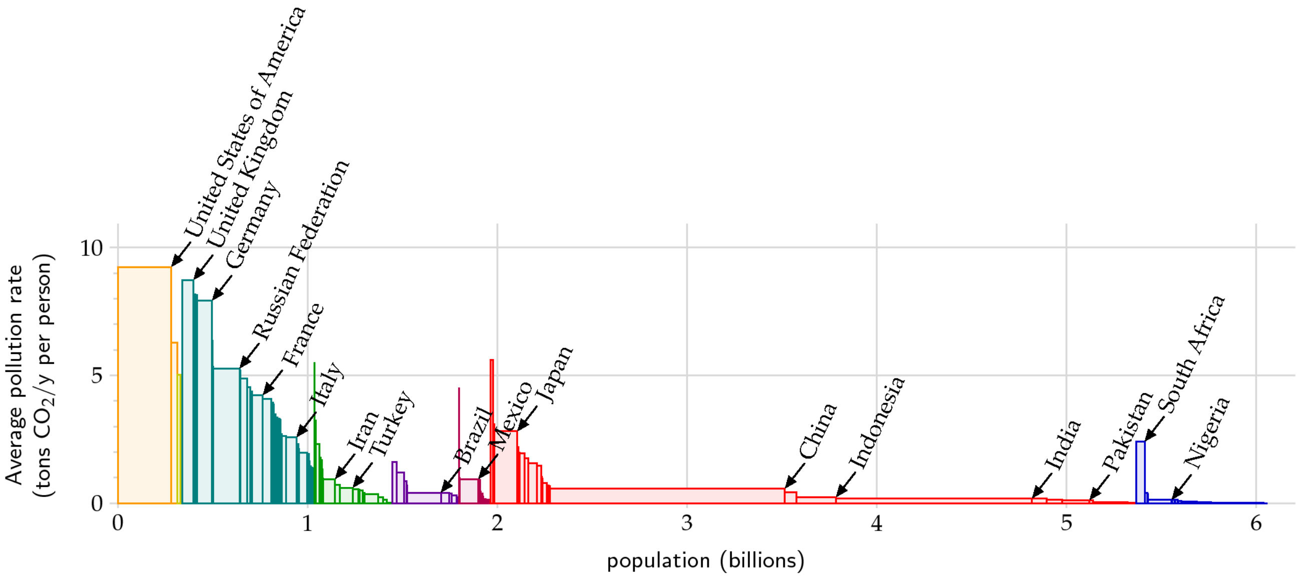
Responsibility by country



Observation: China and India per capita emissions are below the world average! (Bear in mind that much of their industrial emissions are associated with the manufacture of goods for rich countries).

Historical responsibility by country

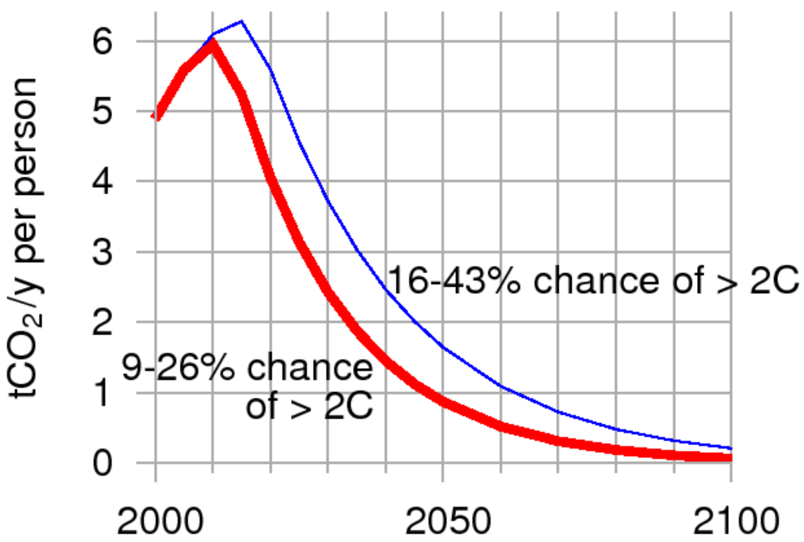
Carbon dioxide remains in the atmosphere for a long time: it is not the rate of CO_2 pollution that matters, it is the cumulative emissions that stay in the atmosphere. Average emission rate over the period 1880-2004:



Observation: figures for the UK and Germany are pretty close to the USA.

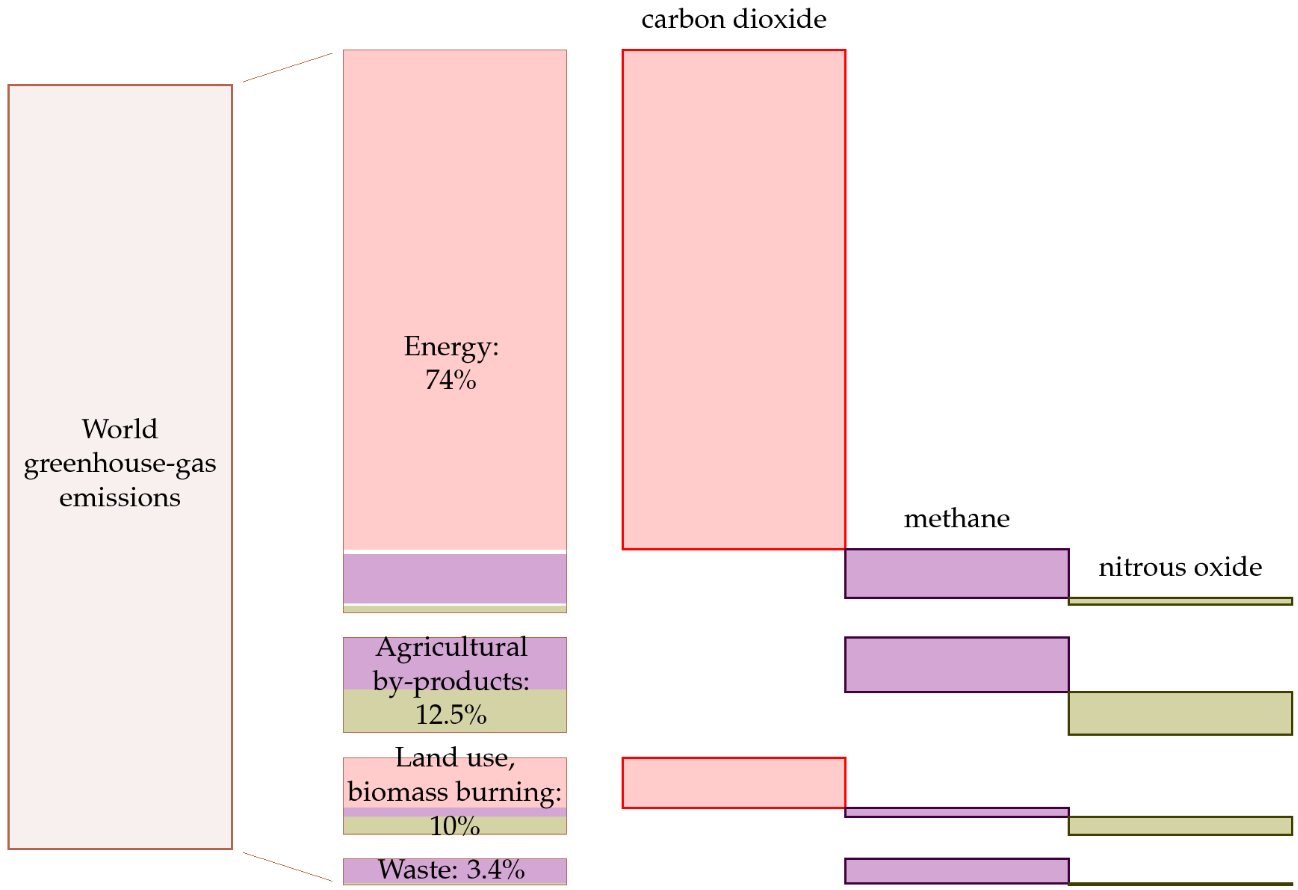
What sorts of cuts in greenhouse gas emission do we need?

Global emissions for two scenarios, expressed in tons of CO_2 per person for a population of six billion, for offering a modest chance of avoiding a 2 °C temperature rise:



These possibly-safe trajectories require global emissions to drop by 70% to 85% by 2050: the UK should reduce CO_2 from 11 tons per year per person to 1 ton per year per person by 2050.

Breakdown of world greenhouse-gas emissions:



Huge cuts are needed in global emissions + breakdown of world greenhouse-gas emissions ⇒ no more fossil fuels.

2. The balance sheet

The question we address in the book: can we conceivably live without fossil fuels?

This will be done through a balance sheet that we will build up progressively:

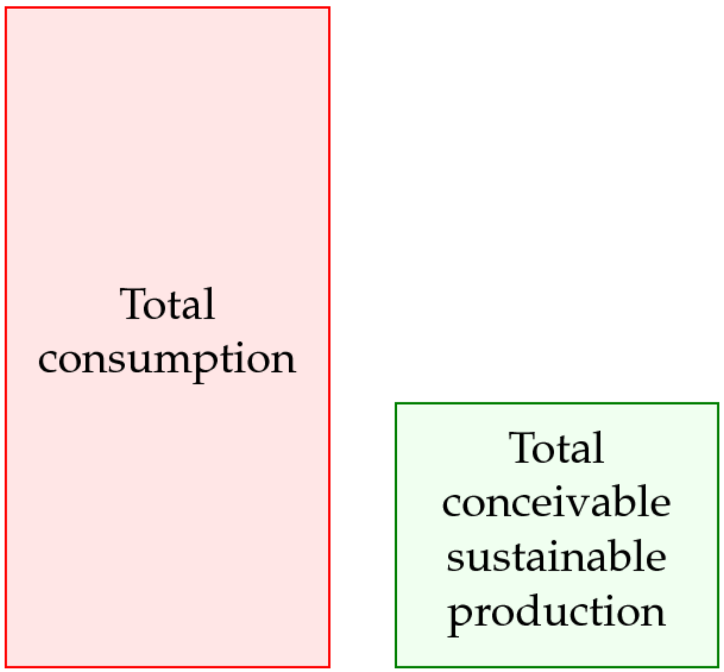
Some key forms of consumption for the left-hand stack will be:

- transport
  - cars, planes, freight
- heating and cooling
- lighting
- information systems and other gadgets
- food
- manufacturing

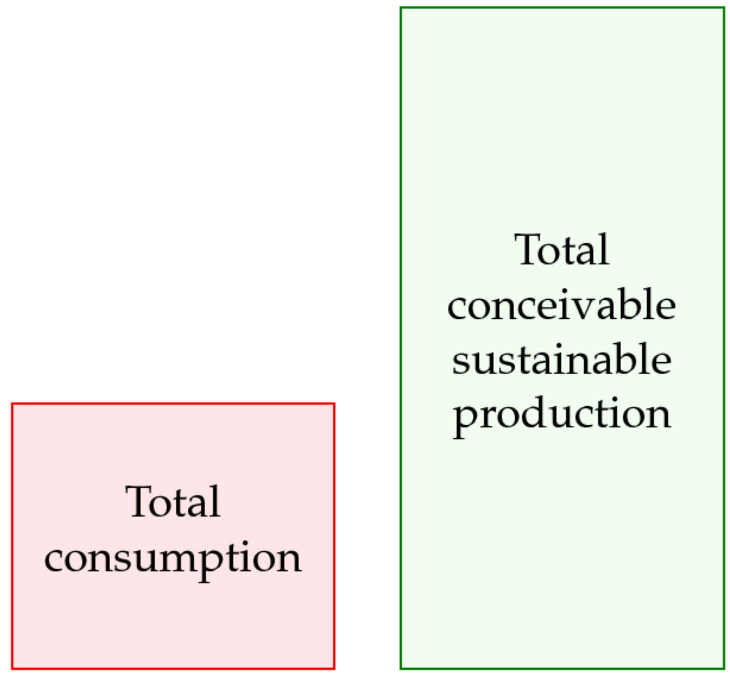
In the right-hand sustainable-production stack, our main categories will be:

- wind
- solar
  - photovoltaics, thermal, biomass
- hydroelectric
- wave
- tide
- geothermal
- nuclear? (with a question-mark, because it's not clear whether nuclear power counts as "sustainable")

The answer will be **NO** if:



The answer will be **YES** if:



Energy and power

Standard units for energy (joule) and power (watt=joule/s) are not convenient here.

Our unit of **energy**: kilowatt-hour (kWh) (1 kWh = 3,6 million joules)

Our unit of **power**: kilowatt-hour (kWh) per day (kWh/d). (40 W $\simeq$ 1 kWh/d)

We also often quote power as **kWh/per day** *per person* so as to better transpose our discussions from one country to another.

The different grades of energy

Energy is always conserved. So, talking of “using” energy does not make a lot of sense. What we really do when using energy is to transform energy from a form that has *low entropy* into a form that has *high entropy*.

We will add labels to the units to distinguish between different grades of energy. One kWh(e) is one kilowatt-hour of electrical energy - the highest grade of energy. One kWh(th) is one kilowatt-hour of thermal energy (the higher the temperature, the lower the entropy). One kWh(ch) is one kilowatt-hour of chemical energy which is also a high-grade energy.

Most of the time, we will talk about energy rather than entropy.

Is it valid to compare different forms of energy such as the chemical energy that is fed into a petrol-powered car with the electricity generated by a wind turbine?

In principle, energy can be converted from one form to another, though conversion entails losses (e.g., fossil fuels used power stations guzzle chemical energy to produce electricity with an efficiency of 40%).

In some summaries of energy production and consumption, different forms of energy are put into the same units but multipliers are introduced (e.g., electrical energy being worth 2.5 times more than the chemical energy in oil).

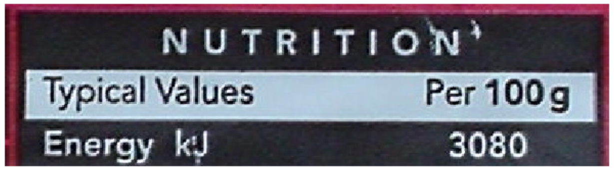
In this class: *one-to-one* conversion rates.

The reason behind this choice: the exchange rate depends on the type of energy that we want. Example: 1kWh of electricity would not be worth 2.5 kWh of chemical energy if we use electricity to make liquid fuels.

3. Cars

$$\text{energy/day} = \frac{\text{distance travelled/day}}{\text{distance/liter of fuel}} \times \text{energy/liter of fuel}$$

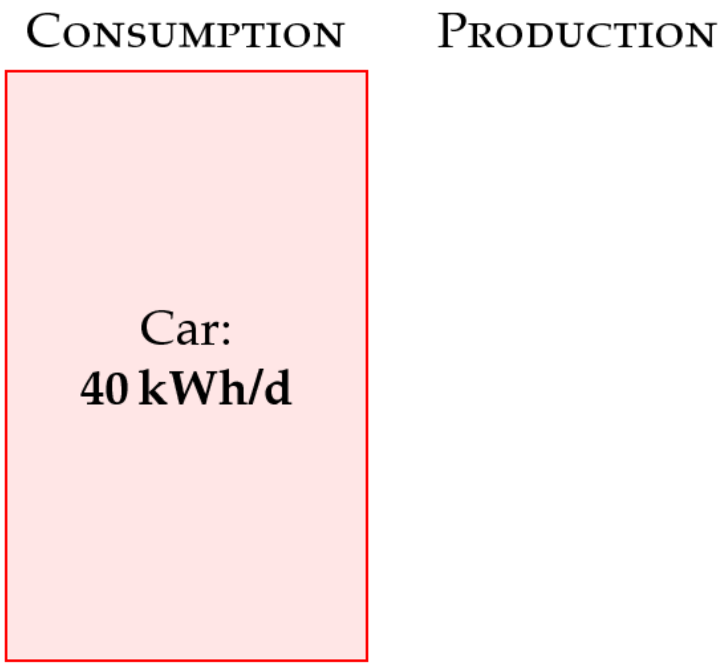
Data/assumptions: (i) distance travelled per day: 50 km (ii) distance per liter of fuel: 12 km (iii) energy per liter of fuel: 10 kWh per liter.



The calorific value of butter, which is also a hydrocarbon, is 3000 kJ per 100 g, or 8 kWh per kg or, assuming a density of 0.8 kg/liter, 7 kWh/liter.

Consumption of a regular car user

$$\text{energy/day} = \frac{50\ \text{km/day}}{12\ \text{km/liter}} \times 10\ \text{kWh/liter}$$
$$\simeq 40\ \text{kWh/day}$$



Notes:

Energy cost of producing the car's fuel. Making one unit of petrol requires an input of 1.4 units of oil.

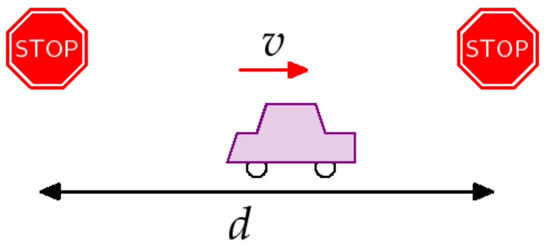
Energy-cost of manufacturing a car. A full chapter will be dedicated to the "energy for making stuff".

Technical notes on cars

Energy used in cars using fossil-fuels goes to four main destinations: (i) speeding up and slowing down by using the brakes (ii) air resistance (iii) rolling resistance (iv) heat - 75% of the energy is wasted as heat.

First scenario analyzed: rolling resistance neglected; car of mass m_c moves at speed v between steps separated by a distance d.

Questions: How does the energy lost in air resistance compare with the energy lost in the brakes? What is the energy consumption of the car? What can be done to reduce the consumption of the car?



Rate at which energy is transferred to the brakes:

$$\frac{\text{kinetic energy}}{\text{time between braking events}} = \frac{\frac{1}{2}m_c v^2}{\frac{d}{v}} = \frac{\frac{1}{2}m_c v^3}{d}$$

Car creates in a time t a tube of air of volume Avt where A is the area of the front view of the car A_{car} multiplied by a *drag coefficient* c_d. The tube has a mass $m_{air} = \rho Avt$ and swirls at a speed v. It has a kinetic energy equal to $\frac{1}{2}\rho Avtv^2$.

Rate of generation of kinetic energy in swirling air:

$$\frac{\text{kinetic energy tube air}}{t} = \frac{1}{2}\rho Av^3$$

Total rate of energy production by the car =
power going into brakes + power going into swirling air =
$\frac{1}{2}m_c v^3/d + \frac{1}{2}\rho A v^3$

• Energy dissipation rate scales as v^3. Energy consumption over a same total distance as v^2.

• Energy lost in air resistance is greater than energy lost in brakes if ratio $(\frac{m_c}{d})/(\rho A)$ is smaller than 1 or, equivalently, if $m_c < \rho A d$.

• **Questions:** [A] What is the special distance d^* between stop signs below which the dissipation is braking dominated and above which it is air swirling? [B] What should be done as a function of d to save energy? [C] Can this simple model explain the 40 kWh/d?

[A]

$$d^* = \frac{m_c}{\rho c_d A_{car}} = \frac{1000\ \text{kg}}{1.3\ \text{kg/m}^3 \times \frac{1}{3} \times 3\ \text{m}^2} = 750\ \text{m}$$

[B] If $d < d^*$ (city driving), it is a good idea if you want to save energy:

1. to reduce the mass of the car
2. to get a car with regenerative brakes
3. to drive slower.

If $d > d^*$, energy dissipation is drag-dominated and can be reduced:

1. by reducing the car's drag coefficient
2. by reducing its cross-sectional area; or
3. by driving slower.

[C] Petrol engines are about 25% efficient $\Rightarrow$ total power of the car $\simeq 4[\frac{1}{2}m_c v^3/d + \frac{1}{2}\rho A v^3]$.
Let us assume v = 110 km/h = 31 m/s and $A = c_d A_{car}$ = 1 m^2 and that d is much greater than d^*. Power consumed by the engine:

$$4 \times \frac{1}{2}\rho A v^3 = 2 \times 1.3\ \text{kg/m}^3 \times 1\text{m}^2 \times (31\ \text{m/s})^3 = 80\ \text{kW}.$$

One hour of travel per day $\Rightarrow$ 80 kWh of energy per day. 55 km per day at this speed $\Rightarrow$ 40 kWh.

Comments:

• If you drive the same distance at half the speed, you reduce your consumption by a factor 4 (provided that the engine has the same efficiency, which is not certain).

• *Could a car consume one hundred times less energy on a motorway and still go at 110 km/h?* No, not if it still has the same shape. At best, its fossil-fuel engine could be slightly more efficient.

Rolling resistance

Rolling resistance is caused by the energy consumed in the tyres and bearings of the car, energy that goes into the noise of wheels against asphalt, energy that goes into grinding the rubber off the tyres, and energy that vehicles put into shaking the ground.

Standard model for rolling resistance: a resistance force $F = C_{rr}N$ where C_{rr} is the rolling resistance coefficient and N the force perpendicular to the surface on which the wheel is rolling ($N = m_c g$ if the vehicle is moving on an horizontal plane). A typical value of C_{rr} for a car is 0.01.

Questions: [A] How much power does the engine need to overcome rolling resistance at a speed $v = 110$ km/h $\simeq 31$ m/s? [B] At which speed is a car's rolling resistance equal to air resistance? Data: (i) $A_{car} = 3$ m^2 (ii) m_c=1000 kg (iii) $c_d = \frac{1}{3}$ (iv) ρ= 1.3 kg/m^3 (v) $C_{rr} = 0.01$ (vi) car moving on an horizontal plane.

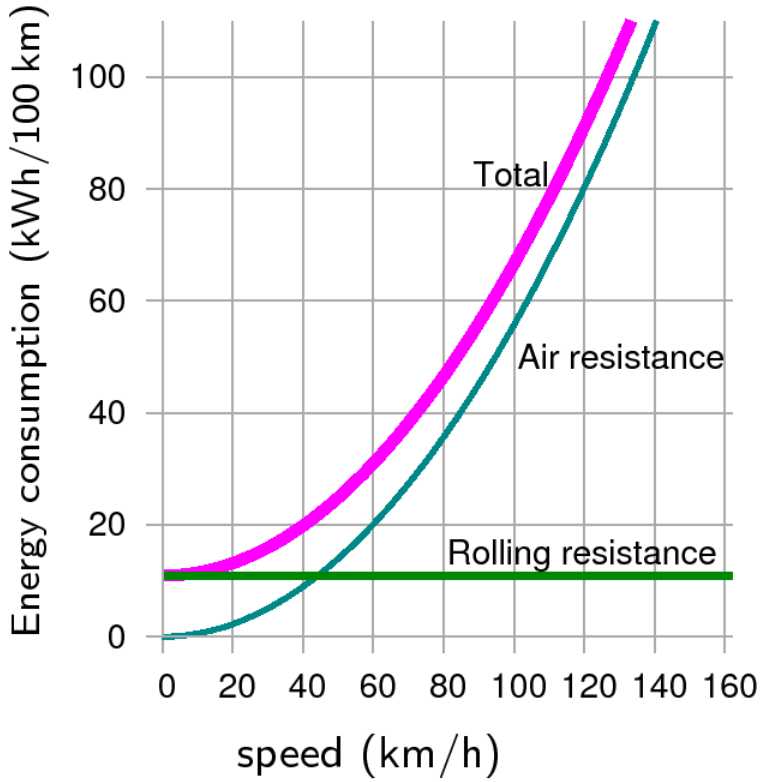
[A] Power required to overcome rolling resistance:

$$\text{force} \times \text{velocity} = 1000 \times 10 \times 0.01 \times 31 = 3100 \text{ W}$$

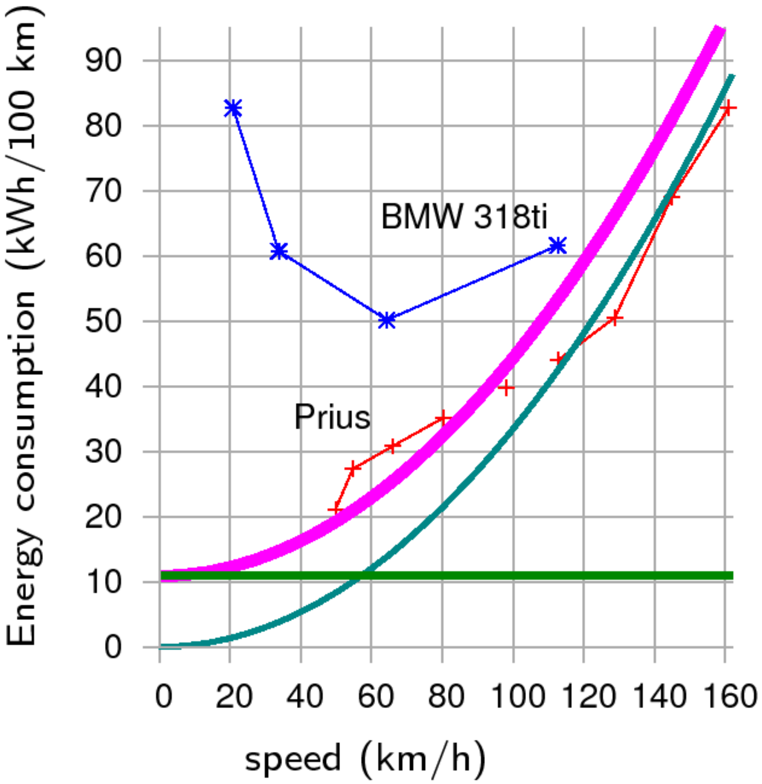
which, allowing for an engine efficiency of 25% requires 12 kW of power for the engine. Power to overcome drag was 80 kW.

[B] Resistances are equal when : $C_{rr} m_c g = \frac{1}{2} \rho c_d A v^2$, that is when:

$$v = \sqrt{2 \frac{C_{rr} m_c g}{\rho c_d A}} \simeq 12.3 \text{ m/s} \simeq 44 \text{ km/h}$$



Simple theory of car fuel consumption. Assumptions: energy efficiency 25%; $c_d A_{car} = 1\ \mathrm{m}^2$; $m_{car} = 1000$ kg and $C_{rr} = 0.01$.

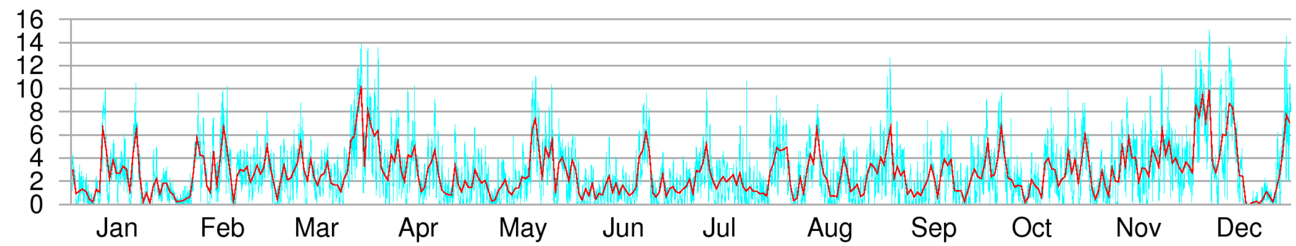


Fuel consumption of current cars. This shows that more conservative speed limits will not necessarily lead to energy savings.

4. Wind

How much on-shore wind power could we plausibly generate?

$$\boxed{\text{power per person} = \text{wind power per unit area} \times \text{area per person.}}$$



Cambridge mean windspeed in m/s, daily (red line) and half-hourly (blue line).

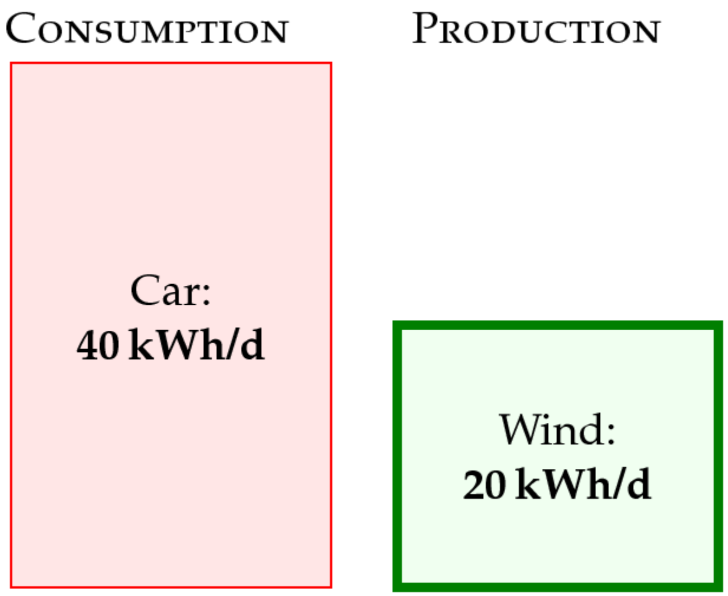
Average wind speed of around 6 m/s $\Rightarrow$ power per unit area of land 2 W.

Question: What is the maximum amount of wind power (in our favorite unit) that can be generated? Data: 250 people per square kilometer.

Answer:

$2\ \mathrm{W/m^2} \times 4000\ \mathrm{m^2/person} = 8000\ \mathrm{W/per\ person} \simeq$ 200 kWh/d per person

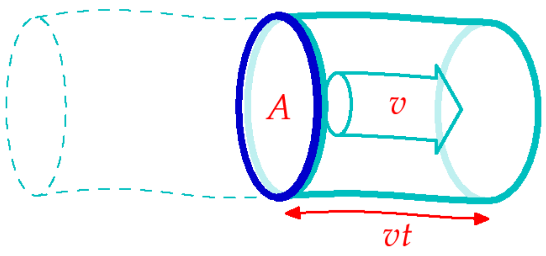
Realistic assumption: only 10% of the country could be covered by windmills $\Rightarrow$ number needs to be reduced to 20 kWh/d per person.



The Whitelee windfarm (near Glasgow):

Description: 140 turbines; covers 55 km^2; *peak* capacity of 322 MW $\Rightarrow$ 6 W/m^2 *peak*. Average amount of power produced is small because turbines do not run at peak output all the time. The ratio of average power to peak power is the load factor. Typical value for a good site with modern turbines: 30% $\Rightarrow$ power production per unit of land for the Whitelee wind farm is $\simeq$ 2 W/m^2.

The physics of wind power



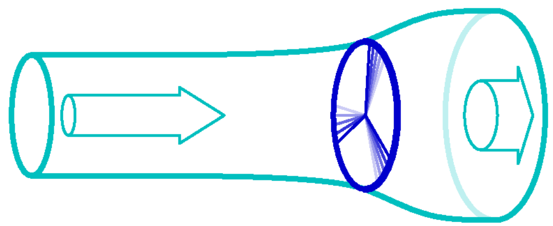
The mass of air that passes through the hoop during a period of time t is equal to $\rho A v t$.

Kinetic energy of that mass of air: $\frac{1}{2}mv^2 = \frac{1}{2}\rho A t v^3 \Rightarrow$ power of the wind for an area A is : $\frac{\frac{1}{2}mv^2}{t} = \frac{1}{2}\rho A v^3$

Question: What is the energy that can be extracted from one square meter of loop? Data: wind speed 6 m/s and density of air 1.3 kg/m^3.

Naive answer: $\frac{1}{2}\rho v^3 = \frac{1}{2} \times 1.3\text{kg/m}^3 \times (6\text{ m/s})^3 = 140\text{ W/m}^2$. But a wind mill cannot extract all the kinetic energy of the air otherwise the slowed-down air would get in the way!

The maximum fraction of energy that can be extracted by a disc-like wind mill: $\frac{16}{27} \simeq 0.59$ (result from a German physicist named Albert Beltz). We assume efficiency to be 50% as efficiency to account for other losses.

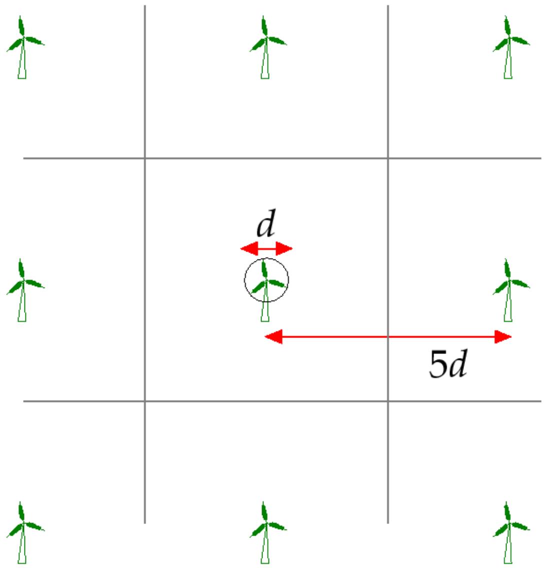


Power of windmill of diameter $d = 25$ m:

$$\begin{aligned} & \text{efficiency factor} \times \text{power per unit area} \times \text{area} \\ = \;& 50\% \times \frac{1}{2}\rho v^3 \times \frac{\pi}{4} d^2 \\ = \;& 50\% \times 140\text{ W/m}^2 \times \frac{\pi}{4}(25\text{ m})^2 = 34\text{ kW} = 816\text{ kWh/d} \end{aligned}$$

How densely could wind mills be packed?

Problem: too close and those upwind will cast wind-shadows on those downwind. Windmills can't be spaced closer than 5 times their diameter without losing significant power.



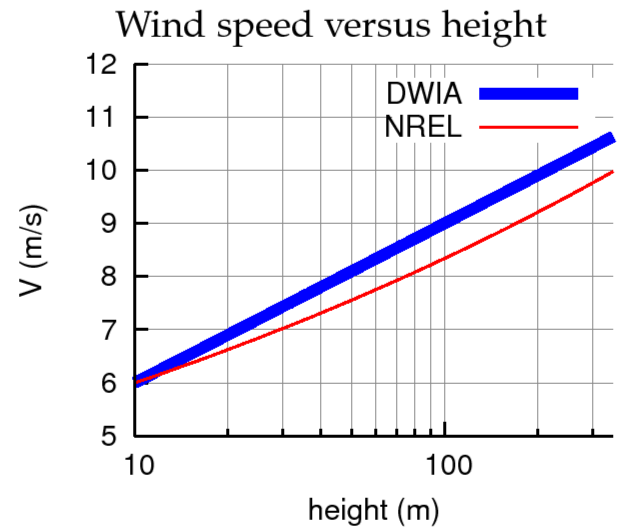
Power that windmills can generate per unit of land:

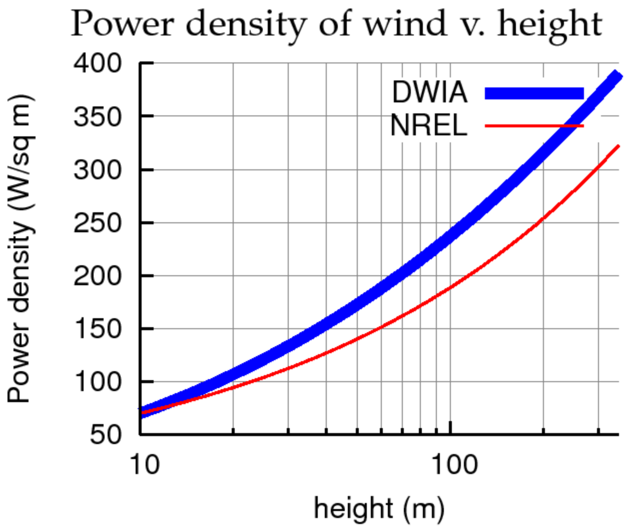
$$\frac{\text{power per wind mill}}{\text{land area per windmill}} = \frac{\frac{1}{2}\rho v^3 \frac{\pi}{8} d^2}{(5d)^2} = 2.2 \text{ W/m}^2$$

Question: Since the answer does not depend on the diameter of the windmill, why are wind mills so big?

Elements of answer: (i) bigger wind mills cost less per MW installed (ii) less land occupation (iii) wind speed increases with height.

1. Wind shear formula from the National Renewable Energy Laboratory (NREL): $v(z) = v_{10}(\frac{z}{10\text{m}})^{\alpha}$ where v_{10} is the speed at 10 m and α typically in $[0.143, \frac{1}{7}]$.
2. Wind shear formula from the Danish Wind Industry Association (DWIA): $v(z) = v_{ref}\frac{\log(z/z_0)}{\log(z_{ref}/z_0)}$ where z_0 is the roughness length (typical value for agricultural land with houses and hedgerows: 0.1 m) and v_{ref} is the speed at a reference height z_{ref}.





Comments

• In our calculations, we used a mean wind speed of 6 m/s. With a mean wind speed of 4 m/s, we must scale our estimate down, multiplying it by $(4/6)^3 \simeq 0.3$.

• In our calculations, we should not have taken the mean wind speed and cubed it; we should have found the mean cube of the windspeed.

• Installing microturbines on roofs is a bad idea. They usually deliver less than 0.2 kWh per day.

The **Enercon E-126** is the largest wind turbine built to date. Technical specificities: bub height of 135 m; rotor diameter of 126 m; can generate up to 7.58 MW of power (or $\frac{7.58 \times 10^6 \times 24}{1000} = 181{,}920$ kWh/d).