Preface

Why are we discussing energy policy?

Three different motivations drive today's energy discussions.

First, fossil fuels are a finite resource. It seems possible that cheap oil (on which our cars and lorries run) and cheap gas (with which we heat many of our buildings) will run out in our lifetime. So we seek alternative energy sources. Indeed given that fossil fuels are a valuable resource, useful for manufacture of plastics and all sort of other creative chemicals, perhaps we should save them for better uses than simply setting fire to them.

Second, we're interested in security of energy supply. Even if fossil fuels are available somewhere in the world, perhaps we don't want to depend on them if that would make our economy vulnerable to the whims of untrustworthy foreigners. (I hope you can hear my tongue in my cheek?) The UK has a particular security-of-supply problem looming, known as the "energy gap". Because a substantial number of old coal power stations and nuclear power stations will be closing down during the next decade, there is a risk that electricity demand will sometimes exceed electricity supply, if adequate plans are not implemented.

Third, using fossil fuels changes the climate. Climate change is blamed on several human activities, but the biggest contributor to climate change is the greenhouse effect produced by carbon dioxide (CO_2). Most of the carbon dioxide emissions come from fossil fuel burning. And the main reason we burn fossil fuels is for energy. So to fix climate change, we need to sort out a new way of getting energy.

Whichever of these concerns motivates you, we need energy numbers, and policies that add up.

The first two concerns are straightforward selfish motivations. The third concern, climate change, is a more altruistic motivation – the brunt of climate change will be borne by future generations over many hundreds of years. Some people feel that climate change is not their responsibility. They say things like "Why should I do anything? China's out of control!" So I'm going to discuss climate change a bit more now, because while writing this book I learned some interesting facts I'd like to pass on. The climate change motivation runs in three steps: one: human fossil-fuel burning causes carbon dioxide concentrations to rise; two: carbon dioxide is a greenhouse gas; three: increasing the greenhouse effect increases average global temperatures.

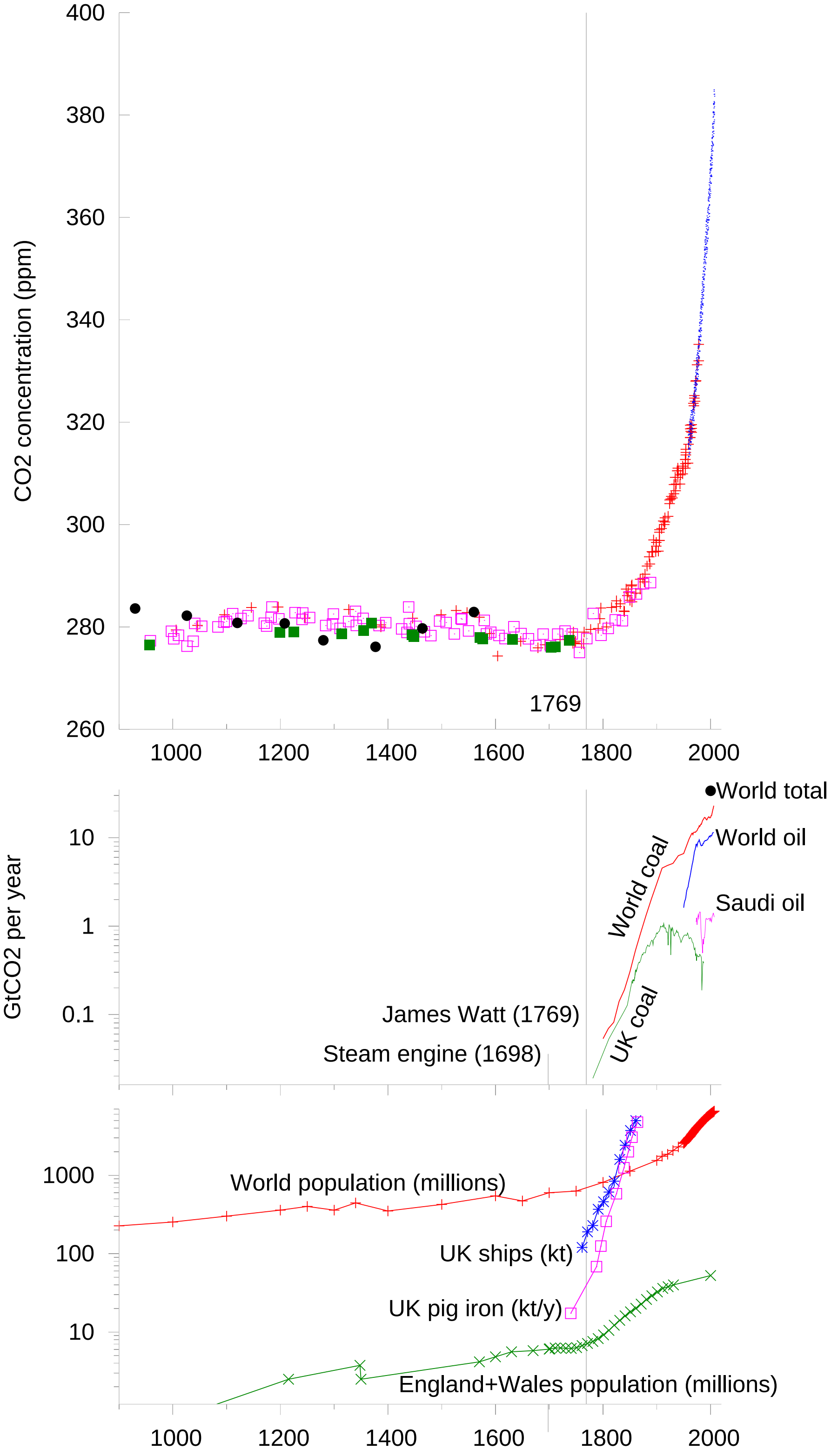


Figure 1. The upper graph shows carbon dioxide (CO_2) concentrations (in parts per million) for the last 1100 years, measured from air trapped in ice cores (up to 1977) and directly in Hawaii (from 1958 onwards). Do you think, just possibly, *something new* may have happened between 1800 AD and 2000 AD?

I've marked the year 1769, in which James Watt patented his steam engine. (The first steam engine was invented in 1698, but Watt's was much more efficient.)

The middle graph shows (on a logarithmic scale) the history of UK coal production, Saudi oil production, world coal production, world oil production, and (by the top right point) the total of all greenhouse gas emissions in the year 2000. All these production rates are shown in billions of tons of CO_2 – an incomprehensible unit, yes, but don't worry: we'll personalize it shortly.

The bottom graph shows (on a logarithmic scale) the population of England, and the world; the history of British pig-iron production (in thousand tons per year); and the tonnage of British ships (in thousand tons).

We start with the fact that carbon dioxide (CO_2) concentrations are rising. The upper graph in figure 1 shows measurements of the CO_2 concentration in the air from the year 1000 AD to the present. Some 'sceptics' have asserted that the recent increase in CO_2 concentration is a natural phenomenon caused by solar activity. Does 'sceptic' mean 'a person who has not even glanced at the data'? Don't you think, just possibly, *something new* may have happened between 1800 AD and 2000 AD? Something that was not part of the natural processes present in the preceding thousand years?

Something did happen, and it was called the Industrial Revolution. I've marked on the graph the year 1769, in which James Watt patented his steam engine. The first steam engine was invented in 1698, and one of its main applications was the pumping of water out of coal mines. It was Watt's more efficient steam engine that really got the Industrial Revolution going. The middle graph shows what happened to British coal production from 1769 onwards, and to world coal production one hundred years later as the Revolution spread. In 1800, coal was used to make iron, to make ships, to heat buildings, to power trains and other machinery, and of course to power the pumps that enabled more coal to be scraped from inside the hills of England and Wales. England was terribly well endowed with coal. When the Revolution started, the amount of carbon sitting in coal under England was roughly the same as the amount sitting in oil under Saudi Arabia. This coal allowed Britain to turn the globe red. The prosperity that came to England and Wales was reflected in a century of unprecented population growth, as the third graph in figure 1 shows. This rate of population growth may have been impressive, but the rate at which coal production grew was even greater. As the middle graph shows, British coal production, which was essentially the same thing as world coal production, doubled every twenty years. Eventually other countries got in on the act too. British coal production peaked in 1910, but meanwhile world coal production continued to doubled every twenty years, a doubling that continued for a total of two hundred years. Coal production is still increasing today. Other fossil fuels are being extracted too – the middle graph in figure 1 shows oil production for example – but in terms of CO_2 emissions, coal is still King.

The burning of fossil fuels is the principal reason why CO_2 concentrations have gone up. This is a fact, but, hang on, do you hear what I hear? I hear a persistent angry buzzing noise coming from a bunch of self-styled sceptics. What can they be saying? Here's Dominic Lawson, a columnist from the *Independent*:

> "The burning of fossil fuels sends about seven gigatonnes of CO_2 per year into the atmosphere, which sounds like a lot. Yet the biosphere and the oceans send about 1900 gigatonnes and 36 000 gigatonnes of CO_2 per year into the atmosphere – ... one reason why some of us are sceptical about the emphasis put on the role of human fuel-burning in the

> greenhouse gas effect. Reducing man-made CO_2 emissions is megalomania, exaggerating man's significance. Politicians can't change the weather."

Now I have a lot of time for scepticism, and not everything that sceptics say is a crock of manure – but irresponsible journalism like Dominic Lawson's deserves a good flushing.

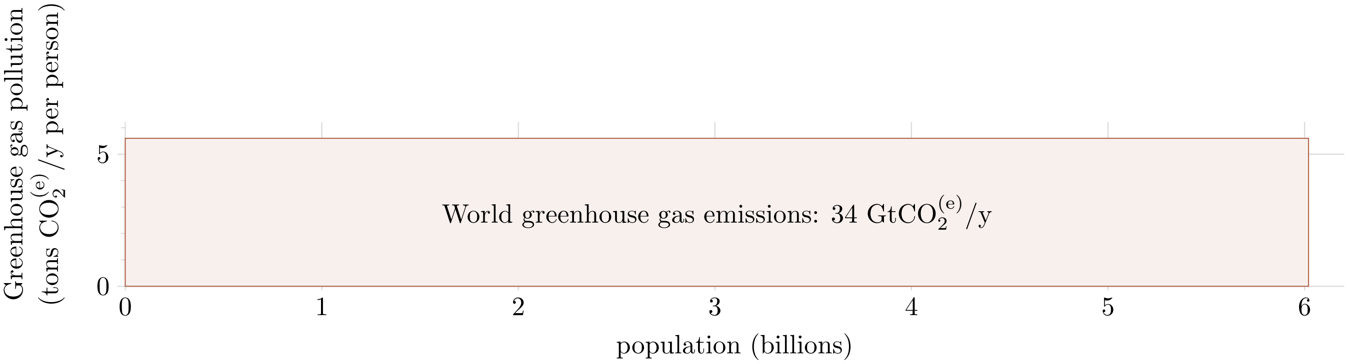
Yes, natural flows of CO_2 *are* much larger than the additional flow we switched on two hundred years ago when we started burning fossil fuels in earnest. But it is terribly misleading to quantify only the large natural flows *into* the atmosphere, failing to mention the almost exactly equal flows *out* of the atmosphere back into the biosphere and the oceans. The point is that the large *natural* flows in and out of the atmosphere have been almost exactly in balance for millenia. So it's not relevant at all that these natural flows are much larger than human emissions. The natural flows *cancelled themselves out.* The natural flows, large though they were, left the concentration of CO_2 in the atmosphere and ocean *constant.* Burning fossil fuels creates a new flow of carbon that, though small, is *not cancelled.* Burning fossil fuels is therefore undeniably changing the CO_2 concentration in the atmosphere and in the surface oceans. No scientist disputes this fact. When it comes to CO_2 concentrations, man is significant.

OK. Fossil fuel burning increases CO_2 concentrations dramatically. Does it matter? "Carbon is nature!", the oilspinners remind us, "Carbon is life!" If CO_2 had no harmful effects, then it would not matter. However, carbon dioxide is a greenhouse gas. Not the strongest greenhouse gas, but a significant one nonetheless. Put more of it in the atmosphere, and it does what greenhouse gases do: it absorbs infrared radiation (heat) heading out from the earth and reemits it in a random direction; the effect of this random redirection of the atmospheric heat traffic is to slightly impede the flow of heat from the planet. Carbon dioxide has a warming effect. This fact is based not on historical records of global temperatures but on the known physical properties of CO_2 molecules. Greenhouse gases are a duvet, and CO_2 is one layer of the duvet.

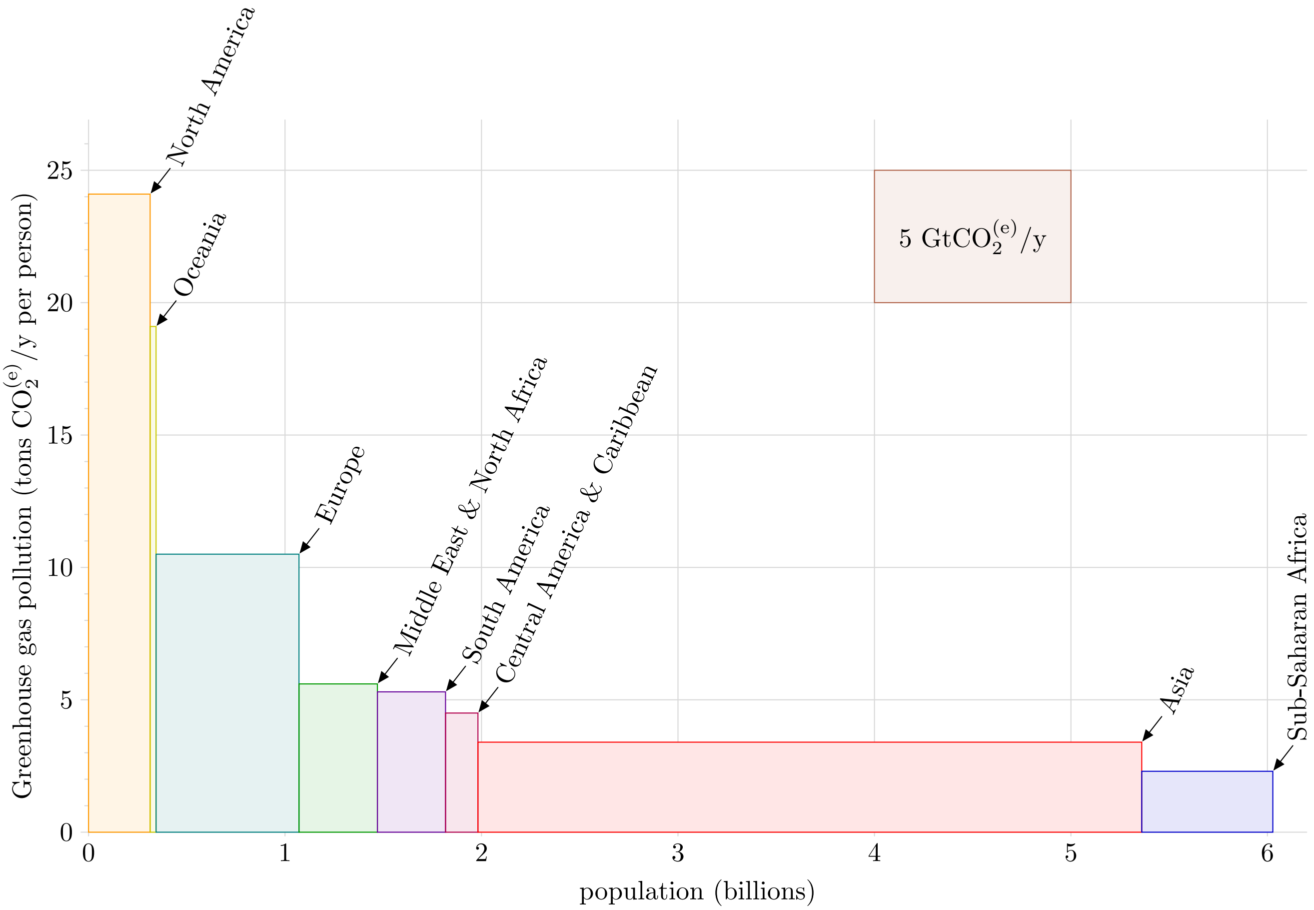
So, if humanity succeeds in doubling or tripling CO_2 concentrations (which is where we are certainly heading, under business as usual), what happens? Here, there is a lot of uncertainty. Climate science is difficult. The climate is a complex, twitchy beast, and exactly how much warming effect CO_2-doubling would have is uncertain. The consensus of the best climate models seems to be that doubling the CO_2 concentration would have roughly the same effect as increasing the intensity of the sun by 2%, and would bump up the global mean temperature by something like 3°C. This would be what historians call *a bad thing.* I won't recite the litany of probable drastic effects, as I am sure you've heard it before. (See `[2z2xg7]` if not.) The litany begins "the Greenland icecap would gradually melt, and, over a period of a few hundred years, sea-level would rise by about 7 metres." The brunt of the litany falls on future generations. Such temperatures have not been seen on earth for 3 million years, and it's conceivable that the ecosystem will be so significantly altered that the earth stops providing some of the goods and services that we currently take for granted.

Climate modelling is very difficult, and I'm not sure any of the models yet made are accurate. But uncertainty about exactly how the climate will respond to extra greenhouse gases is no justification for inaction. If you were riding a fast-moving motorcycle in fog near a cliff-edge, and you didn't have a very good map of the cliff, would the lack of a map justify *not* slowing the bike down?

So, who should slow the bike down? Who is responsible for carbon emissions? Who is responsible for climate change? This is an ethical question, of course, not a scientific one, but ethical discussions must be founded on facts. So let's now explore the facts about present and past greenhouse gas emissions. In the year 2000, world greenhouse gas emissions stood at about 34 billion tons of CO_2 equivalent per year. An incomprehensible number. But we can render it more comprehensible and more personal by dividing by the number of people on the planet, 6 billion, so as to obtain the greenhouse-gas pollution *per person*, which is about 5 or 6 tons per year per person. We can thus represent the world emissions by a rectangle whose width is the population (6 billion) and whose height is the per-capita emissions.



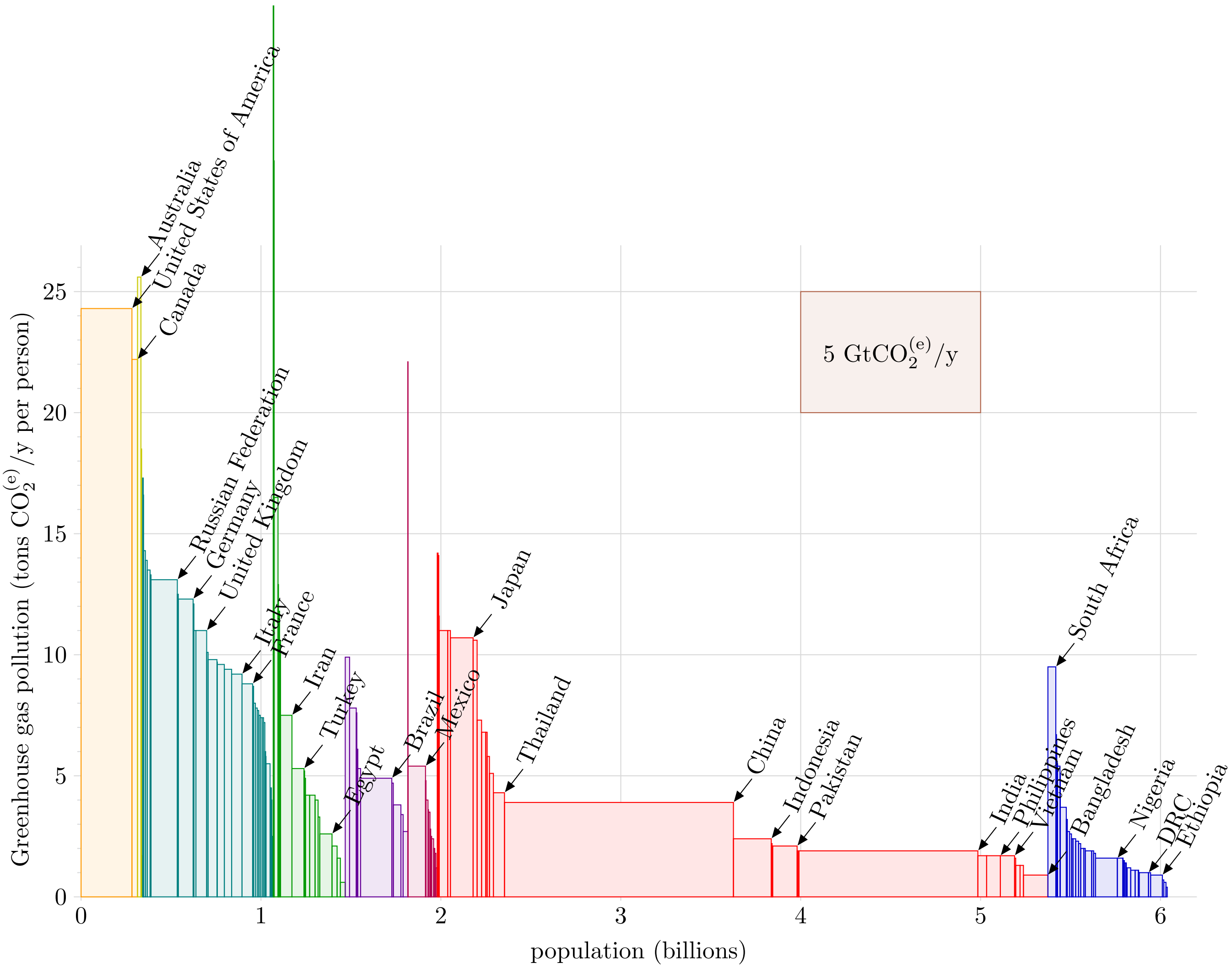
6 tons per year per person is equivalent to every person burning one and a half tons of coal per year. Now, all men are created equal, but some are more equal than others. We don't all emit 6 tons per year. We can break down the emissions of the year 2000, showing how the 34 billion-ton rectangle is shared between the regions of the world.



In this picture I've broken the world down into eight regions. Each rectangle represents the greenhouse gas emissions of one region. The width of the rectangle is the population of the region, and the height is the average per capita emissions in that region.

In the year 2000, Europe's per capita greenhouse gas emissions were twice the world average; and that North America's were four times the world average.

We can continue subdividing, splitting each of the regions into countries. This is where it gets really interesting.

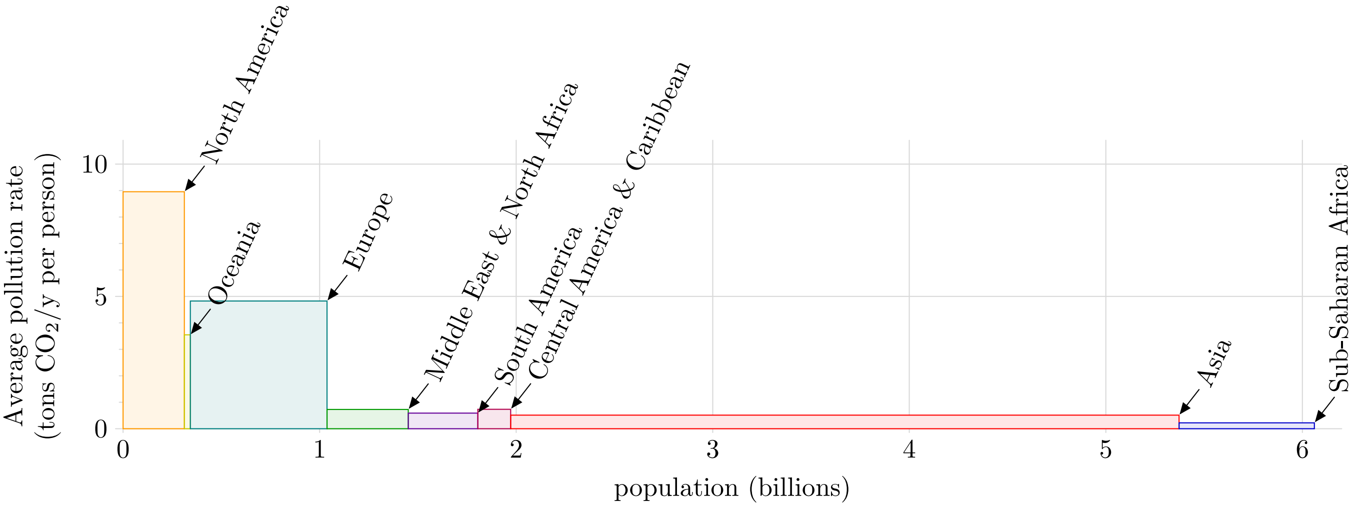


The major countries with the biggest per-capita emissions are Australia, the USA, and Canada. European countries and Japan are notable runners up. Among European countries, the United Kingdom is resolutely average. What about China, that naughty 'out of control' country? Yes, the area of China's rectangle is about the same as the USA's, but the fact is that their per capita emissions are *below* the world average. India's per capita emissions are less than half the world average.

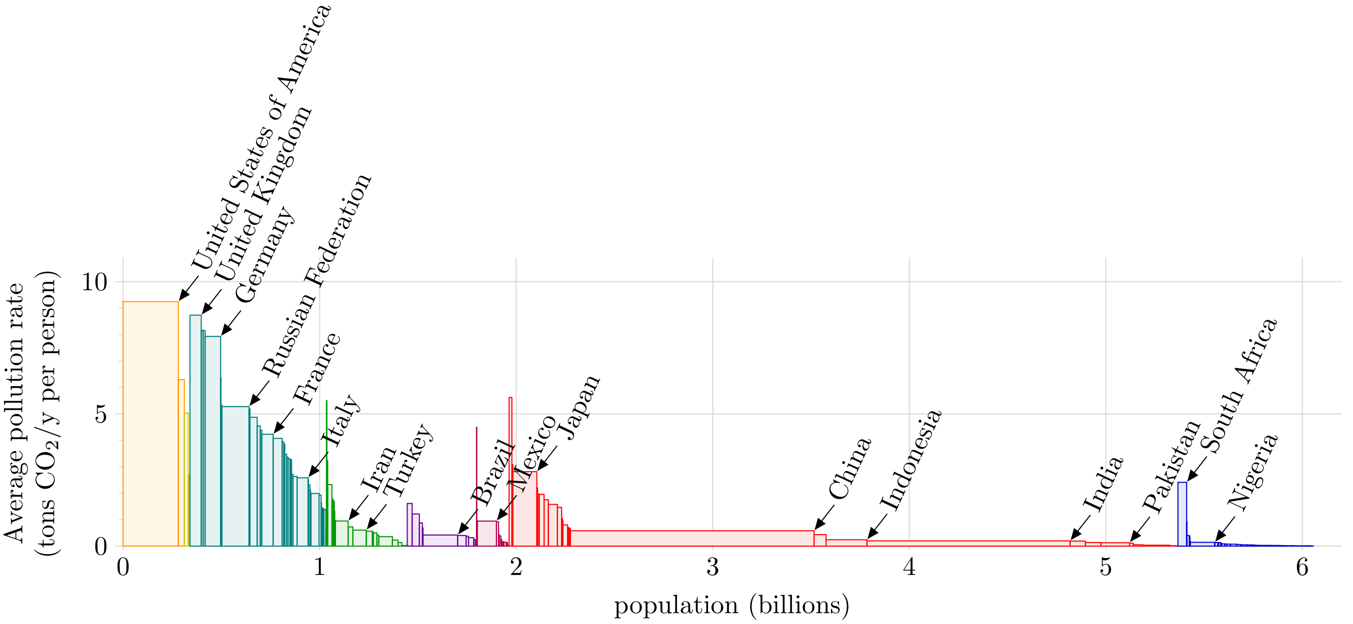
So, assuming that 'something needs to be done' about climate change, assuming that the world needs to reduce greenhouse gas emissions, who has a special responsibility to do something? Well, that's an ethical question. But I find it hard to imagine any system of ethics that denies that the responsibility falls especially on the countries to the left hand side of this diagram, the ones whose emissions are two, three, or four times the world average. Countries like Britain and America for example.

Historical responsibility for climate impact

There's another factual foundation I'd like to explore. If we assume that the climate has been damaged by human activity, and that someone needs to fix it, who should pay? The preceding pictures showed who's doing the polluting today. But it isn't the *rate* of CO_2 pollution that matters so much as the cumulative total emissions – much of the emitted carbon dioxide will hang out in the atmosphere for at least 50 or 100 years. We should therefore ask how big is each country's historical footprint. The next picture shows each region's cumulative emissions of CO_2, expressed as an average emission rate over the period 1880–2004.



When we drill down to the country level, what do we find?



Congratulations, Britain! The UK has made it onto the winners' podium. We may be only an average European country today, but in the table of historical emissions, per capita, we are second only to the USA. [In absolute terms the biggest historical emitters are, in order, USA

(322 $GtCO_2$), Russian Federation (90 $GtCO_2$), China (89 $GtCO_2$), Germany (78 $GtCO_2$), UK (62 $GtCO_2$), Japan (43 $GtCO_2$), France (30 $GtCO_2$), India (25 $GtCO_2$), and Canada (24 $GtCO_2$).]

OK, that's enough ethics. What do scientists say needs to be done, to avoid a risk of giving the earth a 2°C temperature rise over pre-industrial levels? The consensus is clear. We need to get off our fossil fuel habit, and we need to do so fast. Some countries, including Britain, have committed to a 60% reduction in greenhouse-gas emissions by 2050, but we must be clear that such cuts, radical though they are, are unlikely to cut the mustard. If the world's emissions were gradually reduced by 60% by 2050, climate scientists reckon it's more likely than not that global temperatures will rise by more than 2°C. The sort of cuts we need to aim for are shown in figure 2. This figure shows two possibly-safe emissions scenarios presented by Baer and Mastrandrea [2006] in a report from the Institute for Public Policy Research. The lower curve assumes that a decline in emissions starts immediately in 2007, with total global emissions falling at roughly 5% per year. The upper curve assumes a brief delay in the start of the decline, and a 4% drop per year in global emissions. Both scenarios are believed to offer a modest chance of avoiding a 2°C temperature rise. In the lower scenario, the chance that the temperature rise will exceed 2°C is estimated to be 9–26%. In the upper scenario, the chance of exceeding 2°C is estimated to be 16–43%.

These possibly-safe trajectories require global emissions to fall by 70% or 85% by 2050. What would this mean for a country like Britain? If we subscribe to the idea of 'contraction and convergence', which means that all countries aim to have equal per capita emissions, then Britain needs to get down from its current 10 or so tons of CO_2 per year per person to roughly 1 ton per year per person by 2050. This is such a deep cut, I suggest the best way to think about it is 'no more fossil fuels'.

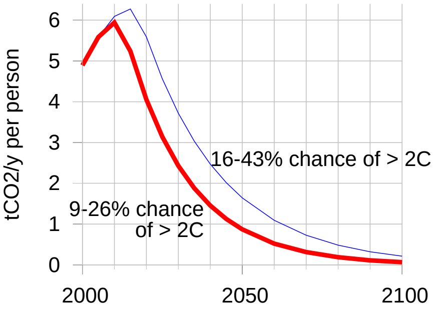


Figure 2. Global emissions for two scenarios considered by Baer and Mastrandrea, expressed in tons of CO_2 per person, using a world population of six billion. Both scenarios are believed to offer a modest chance of avoiding a 2°C temperature rise.

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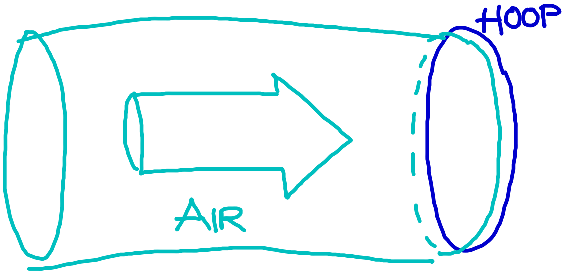
The physics of wind power

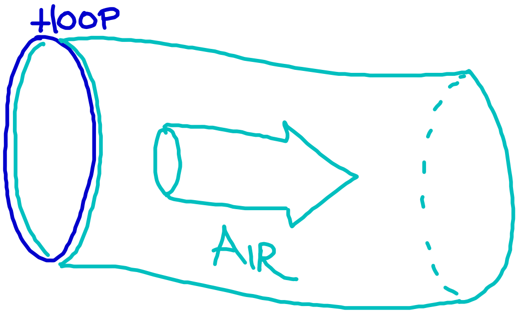
To estimate the energy available from wind, we'll again need one formula: if an object with mass m moves at speed v then its kinetic energy is

$$\frac{1}{2}mv^2.$$

To estimate the energy in wind, let's imagine holding up a hoop with an area of one square metre, facing the wind, whose speed is v. Consider the mass of air that passes through that hoop in one second. Here's a picture of that mass of air just before it passes through the hoop:



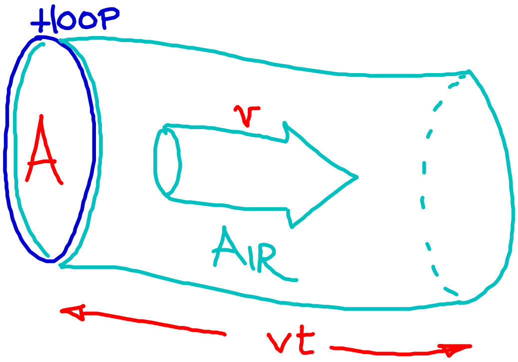
And here's a picture of the same mass of air one second later:



The mass of this piece of air is the product of its density ρ, its area A, and its length, which is v times t, where t is one second.

I'm using this formula:

mass = density × volume



The kinetic energy of this piece of air is

$$\frac{1}{2}mv^2 = \frac{1}{2}\rho Avt\,v^2 = \frac{1}{2}\rho Atv^3. \tag{1.1}$$

So the power of the wind, for an area A – that is, the kinetic energy passing across that area per unit time – is

$$\frac{\frac{1}{2}mv^2}{t} = \frac{1}{2}\rho Av^3. \tag{1.2}$$

This formula may look familiar – we derived an identical expression on p.**??** when we were discussing the power requirement of a moving car.

What's a typical wind speed? On a windy day, a cyclist really notices the wind direction; if the wind is behind you, you can go much faster than normal; the speed of such a wind is comparable to the typical speed of the cyclist, which is, let's say, 21 km per hour (13 miles per hour, or 6 metres per second). In Cambridge, the wind is only occasionally this big. Nevertheless, let's use this as a typical British figure (and bear in mind that we may need to revise our estimates).

miles per hour	km/h	m/s	Beaufort scale
2.2	3.6	1	force 1
7	11	3	force 2
11	18	5	force 3
13	21	6	force 4
16	25	7	
22	36	10	force 5
29	47	13	force 6
36	31	16	force 7
42	68	19	force 8

Figure 1.3. Speeds.

The density of air is about 1.3 kg per m^3. [I usually round this to 1 kg per m^3, which is easier to remember.] Then the typical power of the wind per square metre of hoop is

$$\frac{1}{2}\rho v^3 = \frac{1}{2}1.3\,\mathrm{kg/m^3} \times (6\,\mathrm{m/s})^3 = 140\,\mathrm{W/m^2}. \tag{1.3}$$

Not all of this energy can be extracted by a windmill. The windmill slows the air down quite a lot, but it has to leave the air with *some* kinetic energy, otherwise that slowed-down air would get in the way. Figure 1.4 is a cartoon of the actual flow past a windmill. The maximum fraction of the incoming energy that can be extracted by a disc-like windmill was worked out by a German Physicist called Albert Betz in 1919. If the departing wind speed is one third of the arriving wind speed, the power extracted is 16/27 of the total power in the wind. 16/27 is 0.59. In practice let's guess that a windmill might be 50% efficient. In fact, real windmills are designed with particular wind speeds in mind; if the wind speed is significantly greater than the turbine's ideal speed, it has to be switched off.

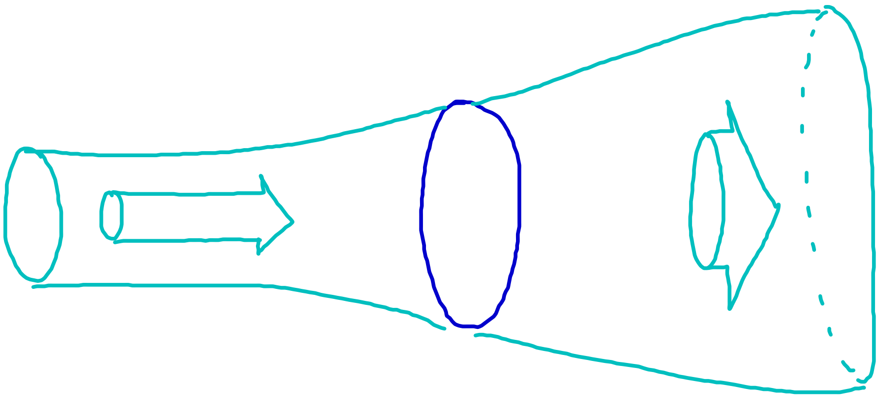


Figure 1.4. Flow of air past a windmill. The air is slowed down and splayed out by the windmill.

As an example, let's assume a diameter of $d = 25$ m, and a hub height of 32 m, which is roughly the size of the lone windmill above the city of Wellington, New Zealand (figure 1.5). The power of a single windmill is

$$
\begin{aligned}
& \text{efficiency factor} \times \text{power per unit area} \times \text{area} \\
= \; & \frac{1}{2} \times \frac{1}{2}\rho v^3 \times \frac{\pi}{4} d^2 && (1.4) \\
= \; & \frac{1}{2} \times 140\,\text{W/m}^2 \times \frac{\pi}{4}(25\,\text{m})^2 && (1.5) \\
= \; & 34\,\text{kW}. && (1.6)
\end{aligned}
$$

Figure 1.5. The Brooklyn windmill above Wellington, New Zealand, with people providing a scale at the base. On a breezy day, this windmill was producing 60 kW, or 1400 kWh per day. Photo by Philip Banks.

Indeed, when I visited this windmill on a good breezy day, its meter showed it was generating 60 kW.

To estimate how much power we can get from wind, we need to decide how big our windmills are going to be, and how close together we can pack them.

How densely could such windmills be packed? Too close and the upwind ones will cast wind-shadows on the downwind ones. Experts say that windmills can't be spaced closer than 5 times their diameter without losing significant power. At this spacing, the power that windmills can generate per unit land area is

$$
\begin{aligned}
\frac{\text{power per windmill}}{\text{land area per windmill}} &= \frac{\frac{1}{2}\rho v^3 \frac{\pi}{8} d^2}{(5d)^2} && (1.7) \\
&= \frac{\pi}{200} \frac{1}{2} \rho v^3 && (1.8) \\
&= 0.016 \times 140\,\text{W/m}^2 && (1.9) \\
&= 2.2\,\text{W/m}^2. && (1.10)
\end{aligned}
$$

This number is worth remembering: a wind farm with a wind speed of 6 m/s produces a power of 2 W per m^2 of land area. Notice that our answer does not depend on the diameter of the windmill. The ds cancelled because bigger windmills have to be spaced further apart. Bigger windmills might be a good idea in order to catch bigger windspeeds that exist higher up (the taller a windmill is, the bigger the wind speed it

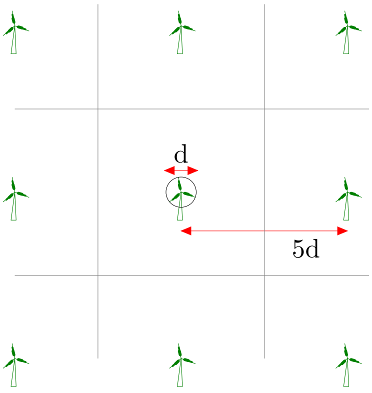


Figure 1.6. Wind farm layout.

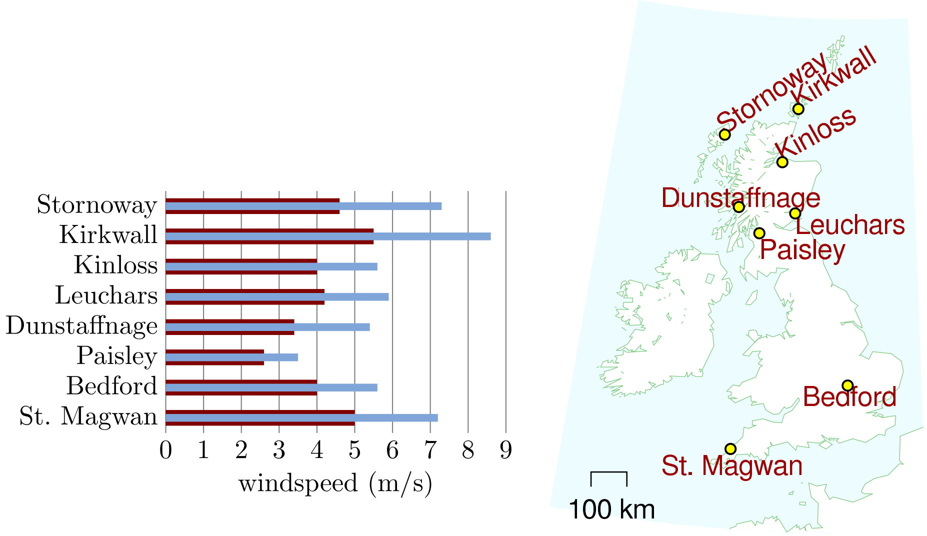


Figure 1.8. Average summer windspeed (dark bar) and average winter windspeed (light bar) in eight locations around Britain.

encounters), or because of economies of scale, but those are the only reasons for preferring big windmills.

This calculation depended sensitively on our estimate of the windspeed. Is 6 m/s plausible as a long-term typical windspeed in windy parts of Britain? Figures **??** and **??** showed windspeeds in Cambridge and Cairngorm. Figure 1.8 shows the mean winter and summer windspeeds in eight more locations around Britain. The mean windspeed in St. Magwan, on the coast of South-west England, the windiest part of England, ranges from 10 knots (5 m/s) to 14 knots (7.2 m/s). In Bedford, a typical town in the middle of England, the mean windspeed ranges from 8 knots (4 m/s) to 11 knots (5.6 m/s) [`ykhss6`]. At Dunstaffnage, on the West coast of Scotland, the mean windspeed ranges from 6.7 knots to 10.6 knots (3.4–5.4 m/s). At Paisley, near Glasgow, the mean windspeed is 5.1 knots in August and 6.9 knots in Winter (2.6–3.5 m/s). At Leuchars, near St. Andrews on the East coast, 8.1 knots in August; 11.4 knots in winter (4.2–5.9 m/s). At Kinloss, in the north-east of Scotland, the mean speed ranges from 7.8 knots to 10.8 knots (4–5.6 m/s). In Stornoway, on the Isle of Lewis, where nothing stops the Atlantic winds, the mean windspeed ranges from 9.0 knots to 14.2 knots (4.6–7.3 m/s). Kirkwall on Orkney has higher average speeds, ranging from 10.7 knots in Summer to 16.8 knots in Winter (5.5–8.6 m/s). (These are the figures at the standard weather-man's height of 10 m; averages are over the period 1971–2000.)

I fear 6 m/s was an overestimate of the typical speed in most of Britain! If we replace 6 m/s by Bedford's 4 m/s as our estimated windspeed, we must revise our estimate down by a factor of $(4/6)^3 \simeq 0.3$. [Remember, wind power scales as wind-speed cubed.]

On the other hand, to estimate the typical power, we shouldn't take the mean wind speed and cube it; rather, we should find the mean cube of the windspeed. The average of the cube is bigger than the cube of the average. But if we start getting into these details, things get even more complicated, because real wind turbines don't actually deliver a power proportional to wind-speed cubed. Rather, they typically have just a range of wind-speeds within which the ideal behaviour holds. At higher or lower speeds real wind turbines deliver less than the ideal power.

Queries

What about micro-generation?

If you plop one of those mini-turbines on your own roof, what energy can you expect it to deliver? Assuming a windspeed of 6 m/s, which, as I said before, is above average for most parts of Britain; and assuming a diameter of 1 m, the power delivered would be 50 W. That's 1.3 kWh per day.

This estimate agrees with the figures for the D400 StealthGen, famously purchased by David Cameron `http://www.d400.co.uk/`, which has a diameter of 1.1 m (and should thus deliver about 1.6 kWh/d at a windspeed 6 m/s). The website says that at windspeeds of 5.1 m/s and 7.7 m/s, this microturbine delivers 40 W and 120 W, respectively. Eclectic Energy encourage the buyer to expect the power produced to be 660 kWh per year (1.8 kWh/d).

Standard windmill properties

The standard windmill of today is typically a machine with a rotor diameter of around 54 metres centred at a height of 80 metres; such a machine has a 'capacity' of 1 MW. The capacity is the *maximum* power the windmill can generate in optimal conditions. Usually, wind turbines are designed to start running at wind speeds somewhere around 3 to 5 m/s and to stop if the wind speed reaches gale speeds of 25 m/s [`ymfbsn`]. The actual average power delivered is the 'capacity' multiplied by a factor that describes the fraction of the time that wind conditions are near optimal. This factor, sometimes called the 'load factor' or 'capacity factor', depends on the site; a typical load factor for a *good* site in the UK is 1/3.

Other people's estimates of wind farm power densities

In `http://www.world-nuclear.org/policy/DTI-PIU.pdf` the UK onshore wind resource is estimated using an assumed wind farm power density of at most 9 MW/km^2, which is 9 W/m^2 (capacity, not average production). If the capacity factor is 33% then the average power production would be 3 W/m^2.

The Whitelee windfarm being built near Glasgow in Scotland has 140 turbines with a combined peak capacity of 322 MW in an area of 55 km^2. That's 5.85 W/m^2, *peak*. If we assume a capacity factor of 33% then the average power production is 2 W/m^2.

The London Array is an offshore wind farm planned for the outer Thames Estuary. With its 1 gigawatt capacity, it is expected to become the world's largest offshore wind farm. The completed wind farm will consist of 271 wind turbines in 245 km^2. `http://www.londonarray.com/london-array-project-introduction/offshore/` and an average power of 3 100 GWh per year (350 MW). Cost £1.5bn. That's a power density of 350 MW/245 km^2 = 1.4 W/m^2. Lower than other offshore farms because, I guess, the site includes a big channel (Knock Deep) that's too deep (about 20 m) for economical planting of turbines.

> *I'm more worried about what these plans [for an electricity substation for the proposed London Array wind farm] will do to this landscape and our way of life than I ever was about a Nazi invasion on the beach.*
>
> Bill Boggia, whose family owns and runs several caravan parks around Graveney, where the undersea cables of the windfarm will come ashore.

Other shapes

Helical wind turbines – they look nice, and they work whatever the wind direction: especially useful in gusty urban environments. The qr5 from `quietrevolution.co.uk` is 5 m high × 3.1 m in diameter, mounted at the top of a 9 m pole. It costs about £33 000 including installation. The turbine weighs approximately 250 kg. Its start-up speed is 4.5 m/s. If the average wind speed is 5.9 m/s, it generates 10 000 kWh per year (27 kWh/d or 1.1 kW, on average). That's 70 W/m^2 of vertical area – about the same as a horizontal-axis turbine. And it has a capital cost of £30 000 per kW average power.

See ocean.tex for power density table.

See **?**, p. 63.

Variation of wind speed with height

Taller windmills see higher wind speeds. The way that wind speed increases with height is complicated, depending on the roughness of the surrounding terrain. As a ballpark figure, doubling the height typically increases wind-speed by 10% and thus increases the power of the wind by 30%.

Some standard formulae for modelling speed v as a function of height z are:

1. According to the wind shear formula from NREL [`ydt7uk`], the speed is modelled as a power of height:

$$v(z) = v_{10}\left(\frac{z}{10\,\mathrm{m}}\right)^{\alpha}$$

where v_{10} is the speed at 10 m, and a typical value of the exponent

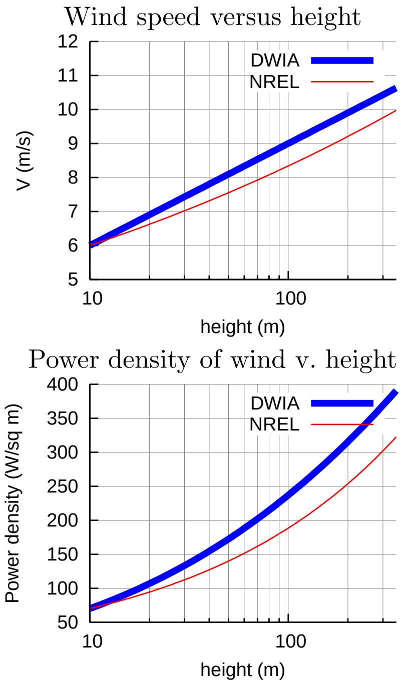


Figure 1.9. Two models of wind speed and wind power as a function of height. For each model the speed at 10 m has been fixed to 6 m/s. For the Danish Wind model, the roughness length is set to $z_0 = 0.1$ m.

α is 0.143 or 1/7. Thus

$$v(z) \propto z^{1/7}.$$

This one-seventh law is used by **?**, for example.

2. The wind shear formula from the Danish Wind Energy Association [`yaoonz`] is

$$v(z) = v_{\text{ref}} \frac{\log(z/z_0)}{\log(z_{\text{ref}}/z_0)},$$

where z_0 is a parameter called the roughness length, and v_{ref} is the speed at a reference height z_{ref} such as 10 m. The roughness length for typical countryside (agricultural land with some houses and sheltering hedgerows with some 500 m intervals – 'roughness class 2') is $z_0 = 0.1$ m.

In practice, these two wind shear formulae give very similar numerical answers.

Money

The approximate cost for a Vestas V52-850 kW turbine is between $500,000 and $1,000,000.

Accidents

`http://www.caithnesswindfarms.co.uk/` has data on wind fatalities and accidents. 45 fatalities since the 1970s, 17 in 2000–2006.

102 blade failure incidents. Pieces of blade travel 400 m.

Structural failures: 40 during 1998–2006.

`http://www.timesonline.co.uk/tol/news/world/asia/article687157.ece` A set of wind turbines in Tsukuba City, Japan, so bad that they were actually importing more than they were exporting. Their installers were so embarrassed by the stationary turbines that they imported power to make them spin so that they looked like they were working!

Netherlands wind capacity factor: 22%; Germany: 19%.

11 MAXIMUM FRACTION OF THE INCOMING ENERGY THAT CAN BE EXTRACTED BY A DISC-LIKE WINDMILL WAS WORKED OUT BY A GERMAN PHYSICIST CALLED ALBERT BETZ There is a nice explanation on the Danish Wind Industry Association's website. [`yekdaa`].

? say a minimum annual mean wind speed of 7.0 m/s is currently thought to be necessary for commercial viability of wind power. About 33% of UK land area has such speeds.

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