Sustainable Energy – without the hot air

Further notes

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Preface to notes

This document is a collection of half-baked notes that were part of David MacKay's 'Sustainable Energy – without the hot air'.

Part I

Carbon

So far, this book's question has been 'how can we live without fossil fuels?' Because Britain currently gets 90% of its energy from fossil fuels, it's no surprise that getting off fossil fuels requires big, big changes – a total change in the transport fleet; a complete change of most building heating systems; and a ten- or twenty-fold increase in wind power and nuclear power, for example.

Given the current lack of understanding of the size of these required changes, and the general tendency of the public to say 'no' to wind farms, 'no' to nuclear power, 'no' to tidal barrages – 'no' to anything other than fossil fuel power systems – I am worried that we won't actually get off fossil fuels when we need to. I am concerned that we'll just settle for half-measures: 10% more efficient fossil-fuel-burning power stations, cars, and home heating systems; a fig-leaf of a carbon trading system; a sprinkling of wind turbines.

This part of the book offers some straight answers about carbon: if we carry on burning fossil fuels for another 50 years, and then think about trying to switch to low-carbon technologies, will things be OK? who are the big carbon emitters who are responsible for the change in atmospheric CO_2 concentrations? what sort of legislation is needed to bring about a switch to a truly low-carbon society? what does the price of carbon need to be, to bring about this switch? and if we don't switch now, what is the energy cost of cleaning up CO_2 pollution later?

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Climate change

> We, humanity, cannot release to the atmosphere all, or even most, fossil fuel CO_2. To do so would guarantee dramatic climate change, yielding a different planet…
>
> *J. Hansen et al* (2007).

> "Avoiding dangerous climate change" is impossible – dangerous climate change is already here. The question is, can we avoid *catastrophic* climate change?
>
> *David King, Chief Scientist*, 2007

When I first planned this book, my intention was to ignore climate change altogether. In some circles, 'is climate change happening?' was a controversial question. As were 'is it caused by humans?' and 'does it matter?'. And, dangling at the end of a chain of controversies, 'what should we do about it?'. I felt that sustainable energy was a compelling issue by itself, and it was best to avoid controversy. My argument was to be: 'never mind when fossil fuels are going to run out; never mind whether climate change is happening; *burning fossil fuels is not sustainable*; let's imagine living sustainably, and think how much sustainable energy is available.'

However, climate change has risen into public consciousness, and it raises all sorts of interesting back-of-envelope questions. So I decided to discuss it after all.

Pollution

A major waste-product of the energy industry is carbon dioxide (CO_2). If this waste-product had no harmful effects, then it would not matter. However, there is widespread agreement that carbon dioxide is a pollutant, causing climate change. Exactly how much warming effect CO_2

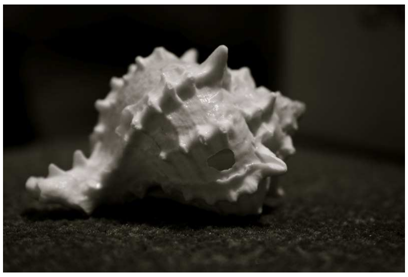
has is uncertain, but the fact that it has a warming effect is not in dispute. This fact is based not on historical records of global temperatures but on the known physical properties of CO_2 molecules. Carbon dioxide is a greenhouse gas.

In the past, such pollution was effectively permitted for free. It's now widely agreed that allowing people to pollute for free is an unwise policy.

To figure out what form a wise policy on carbon pollution should take, we need a rough model of CO_2, where it is, where it's going and the timescales on which it goes from A to B.

Once this rough model is laid out, we'll address the following questions.

- Is there a 'safe' level of carbon pollution, and if so, what is it?
- What are the energy costs of undoing carbon pollution? Does it actually cost more energy to clean up carbon pollution than the energy that was obtained when the carbon was emitted?
- If a carbon tax is introduced, what price would be required (per tonne of CO_2) to pay for cleaning up carbon pollution? And what price would be required to have an appreciable influence on the behaviour of energy consumers, so that they pollute less?
- What price on CO_2 would be required to allow us to abolish the government's current carbon-insensitive taxes (for example income tax and VAT) and replace them with carbon taxes?



Understanding CO_2

Where is all the carbon? And where is the CO_2?

We need to know how much is in the oceans, ground, and vegetation, compared to the atmosphere if we want to understand the results of CO_2 emissions.

If nearly all of the CO_2 is in the atmosphere, then tripling the CO_2 concentration in the atmosphere would be a mistake that nature could not reverse.

If nearly all of the CO_2 is in the oceans, then tripling the CO_2 concentration in the atmosphere might be a reversible mistake – if we subsequently stopped emitting CO_2, the oceans would gradually mop up CO_2, and the CO_2 concentration might return close to its original levels (after perhaps a few centuries of catastrophic climate change).

Units

Just as energy is measured in many different units, there is no single established unit for quantities of carbon. Carbon pollution charges are

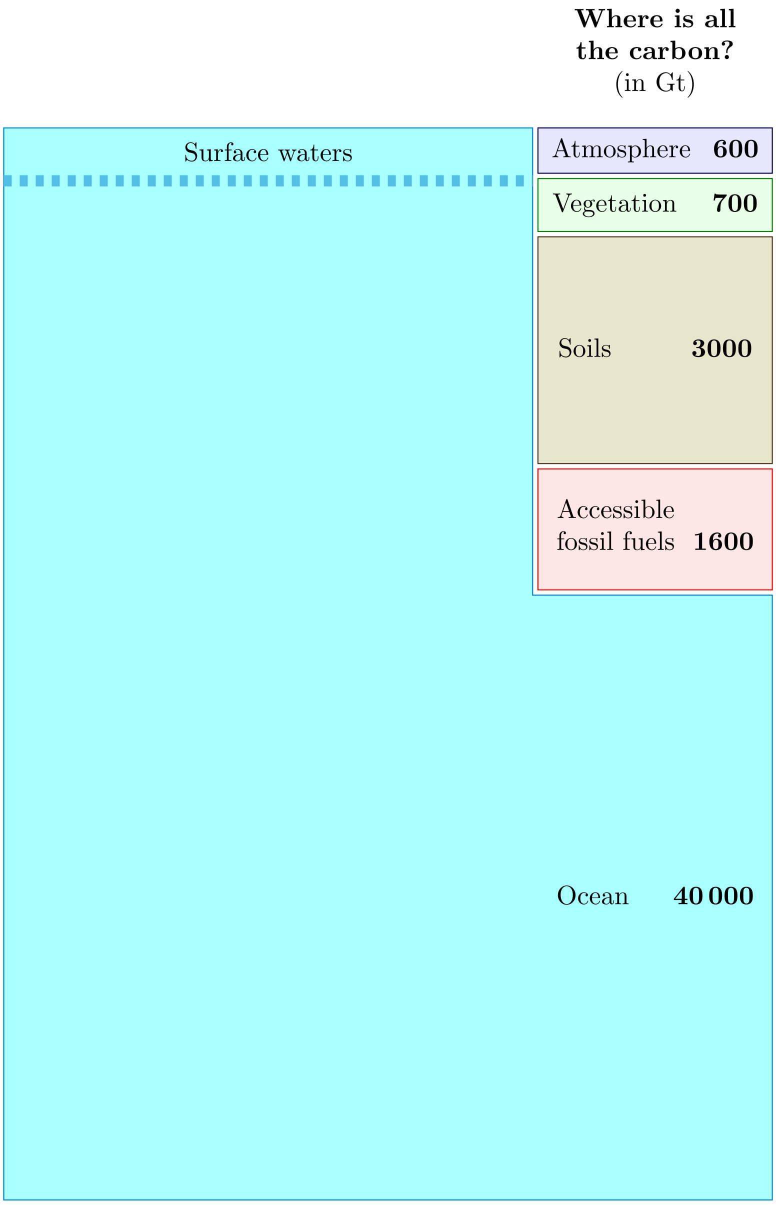


Figure 1.1. Estimated amounts of carbon, in gigatonnes, in accessible places on the earth. (There's a load more carbon in rocks too; this carbon moves round on a timescale of millions of years, with a long-term balance between carbon in sediment being subducted at tectonic plate boundaries, and carbon popping out of volcanos from time to time. For simplicity I ignore this geological carbon.)

usually measured in dollars or euros per ton of CO_2, so I'll use the **ton of CO_2** as the main unit when talking about personal carbon pollution, and the **ton of CO_2 per year** to measure rates of pollution. But when talking about carbon in fossil fuels, vegetation, soil, and water, I'll talk about tons of carbon.

One ton of CO_2 contains 12/44 tons of carbon, a bit more than a quarter of a ton. On a planetary scale, I'll talk about gigatons of carbon (GtC). A gigaton of carbon is a billion tonnes, also known as a petagram (Pg). Gigatons are hard to imagine, but if you want to bring it down to a human scale, imagine burning one ton of coal (which is what you might use to heat a house over a year). Now imagine everyone on the planet burning one ton of coal per year: that's 6 GtC per year, because the planet has 6 billion people.

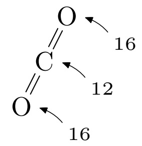


Figure 1.2. The weights of an atom of carbon and a molecule of CO_2 are in the ratio 12 to 44, because the carbon weighs 12 units and the two oxygens weigh 16 each. $12 + 16 + 16 = 44$.

Where is the carbon?

Figure 1.1 shows where the carbon is. Most of it – 40 000 Gt – is in the ocean (in the form of dissolved CO_2 gas, carbonates, living plant and animal life, and decaying materials). Soils and vegetation together contain about 3000 Gt. Accessible fossil fuels – mainly coal – contain about 1600 Gt. Finally, the atmosphere contains about 600 Gt of carbon.

Until recently, all these pools of carbon were roughly in balance: all flows of carbon out of a pool (say, soils, vegetation, or atmosphere) were balanced by equal flows into that pool. The flows into and out of the fossil fuel pool were both negligible. Then humans started burning fossil fuels. This added an extra unbalanced flow, as shown in figure 1.3.

The rate of fossil fuel burning was roughly 1 GtC/y in 1920, 2 GtC/y in 1955, and 7 GtC in 2006. (These figures include a small contribution from cement production, which releases CO_2 from limestone.) (Actually, according to the latest papers, emissions in 2006 were 9.9 GtC, of which 8.4 GtC were fossil fuels.)

How has this significant extra flow of carbon modified the picture shown in figure 1.1? Well, it's not exactly known. Figure 1.3 shows the key things that are known. The extra 7 GtC per year that we're putting in the atmosphere has elevated the atmospheric concentration of carbon enough that there is now a net flow of CO_2 from the atmosphere into the oceans, amounting to 2 GtC per year. (Recent research indicates this carbon-uptake by the oceans may be reducing.) Some extra carbon is moving into vegetation and soil too, perhaps about 1.5 GtC per year, but these flows are less well measured. What is certain is that continued carbon pollution at a rate of 7 GtC per year will continue to increase CO_2 levels in the atmosphere, and in the surface waters.

What is the long-term destination of the extra CO_2? Well, since the amount in fossil fuels is so much smaller than the total in the oceans, 'in the long term' the extra carbon will make its way into the ocean, and the amounts of carbon in the atmosphere, vegetation, and soil will

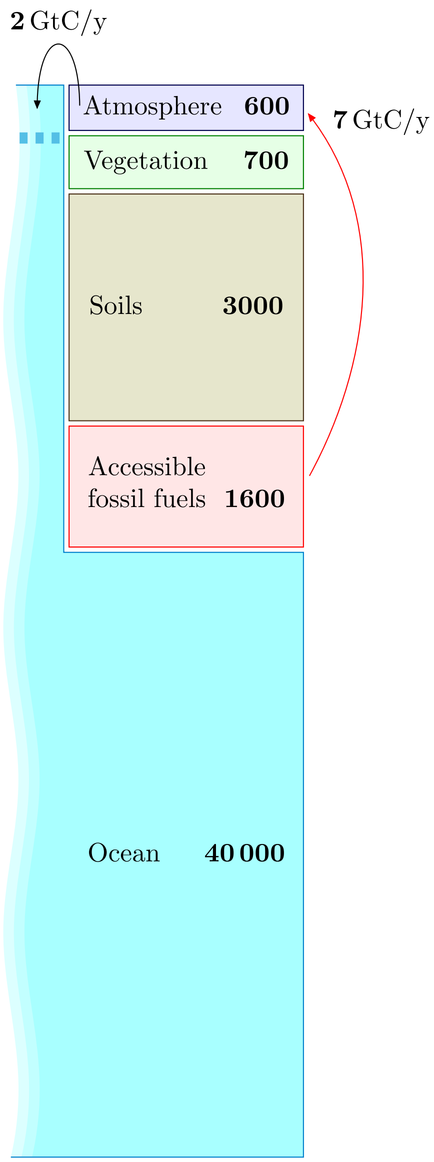


Figure 1.3. The arrows show the extra carbon flows produced by burning fossil fuels. There is a net 5 GtC/y imbalance between the 7 GtC/y emissions into the atmosphere from burning fossil fuels and the 2 GtC/y take-up of CO_2 by the oceans. This cartoon omits the less-well quantified flows between atmosphere, soil, vegetation, and so forth. The other omitted flows between compartments are large, and important to an accurate model of climate, but I recklessly ignore

return to normal. However, 'the long term' means thousands of years. Equilibration between atmosphere and the *surface* waters is rapid, taking only a few tens of years. But figures 1.1 and 1.3 show a dashed line separating the surface waters of the ocean from the rest of the ocean. On a time-scale of fifty years, this boundary is virtually a solid wall. Radioactive carbon dispersed across the globe by the atomic bomb tests of the 1970s has penetrated the oceans to a depth of only about 400 m. In contrast the average depth of the oceans is about 4000 m.

The oceans circulate slowly: a chunk of deep-ocean water takes about 1000 years to roll up to the surface and down again. The circulation of the deep waters is driven by a combination of temperature gradients and salinity gradients, so it's called the thermohaline circulation. (In contrast to the circulations of the surface waters, which are wind-driven.)

This slow turn-over of the oceans has a crucial consequence: we have enough fossil fuels to seriously influence the climate over the next thousand years.

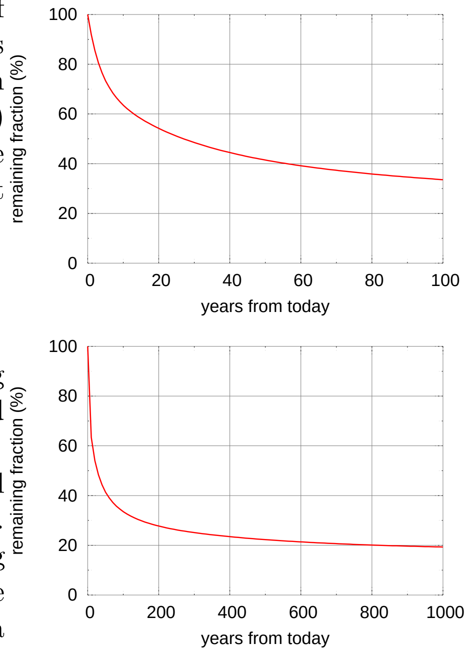


Figure 1.4. Decay of a small pulse of CO_2 added to today's atmosphere, according to the Bern model of the carbon cycle.

Where is the carbon going

Figure 1.3 is a gross simplification. For example, humans are causing additional flows not shown on this diagram: the burning of peat and forests in Borneo in 1997 alone released about 0.7 GtC.

Nevertheless, this cartoon helps us understand roughly what will happen in the short term and the medium term under various policies. First, if carbon pollution follows a 'business as usual' trajectory, burning another 500 Gt of carbon over the next 50 years, we can expect the carbon to trickle gradually into the surface waters of the ocean at a rate of 2 GtC per year initially, and perhaps at a rising rate as the atmospheric concentration increases. By 2055, at least 100 Gt of the 500 would have gone into the surface waters, and CO_2 concentrations in the atmosphere would be roughly double their pre-industrial levels.

If carbon pollution were halted in the 2050s, much of the 500 Gt we put into the atmosphere would gradually drift into the surface oceans over the subsequent 50 or 100 years. As the surface waters' carbon concentration increased by 10% or so, atmospheric concentrations of carbon would eventually fall back towards current levels. Business as usual (for the next 50 years) thus puts the planet on track to a period (from 2050 to at least 2100) during which atmospheric carbon concentrations will be double their pre-industrial levels. Such atmospheric concentrations have not been seen on earth for 50 million years, and would very likely cause difficulties for billions of humans, not to mention other species.

And that's assuming that this large perturbation of the atmosphere doesn't drastically alter the ecosystem. It's conceivable, for example, that the acidification of the surface waters of the ocean might cause a sufficient extinction of ocean plantlife that a new vicious cycle kicks in: acidification means extinguished plantlife, means plantlife absorbs

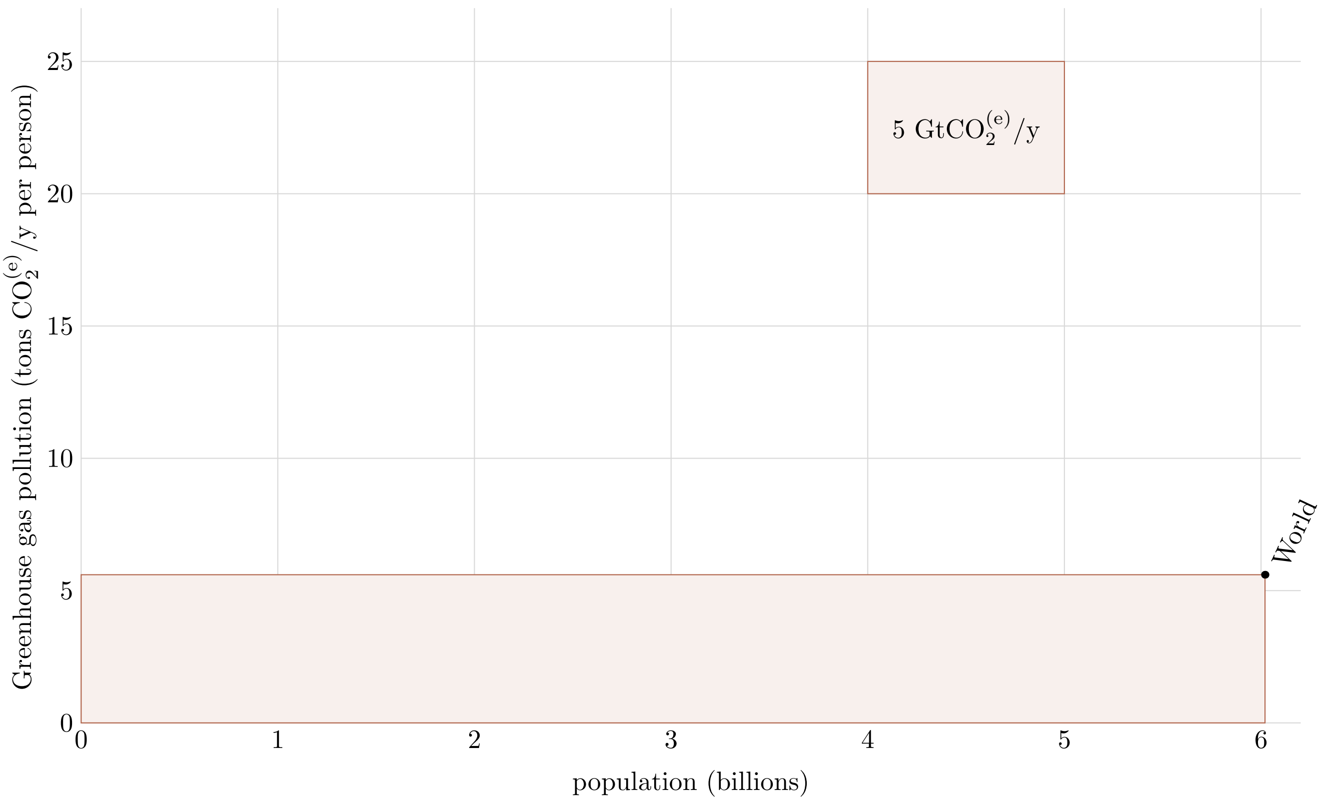


Figure 1.5. Total greenhouse gas emissions, 2000 = $34\,GtCO_2^{(e)}$.

less CO_2 from the ocean, means oceans become even more acidic. Such vicious cycles (which boffins call 'positive feedbacks' or 'runaway feedbacks') have happened on earth before: it's believed, for example, that ice ages ended relatively rapidly because of positive feedback cycles in which rising temperatures caused surface snow and ice to melt, which reduced the ground's reflection of sunlight, which led to increased temperatures. Another positive feedback possibility to worry about involves methane hydrates. Global warming greater than 1°C would melt methane hydrates, which release methane into the atmosphere, which increases global warming more strongly than CO_2.

This isn't the place to discuss the uncertainties of climate change in any more detail. I highly recommend the books 'Avoiding Dangerous Climate Change' and 'Global Climate Change'.

Where the carbon's coming from

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

When I show this figure, someone usually asks 'who's the green spike in the Middle East?'. The green, super-Australian, super-American spike is made up of Qatar, United Arab Emirates, and Kuwait, whose

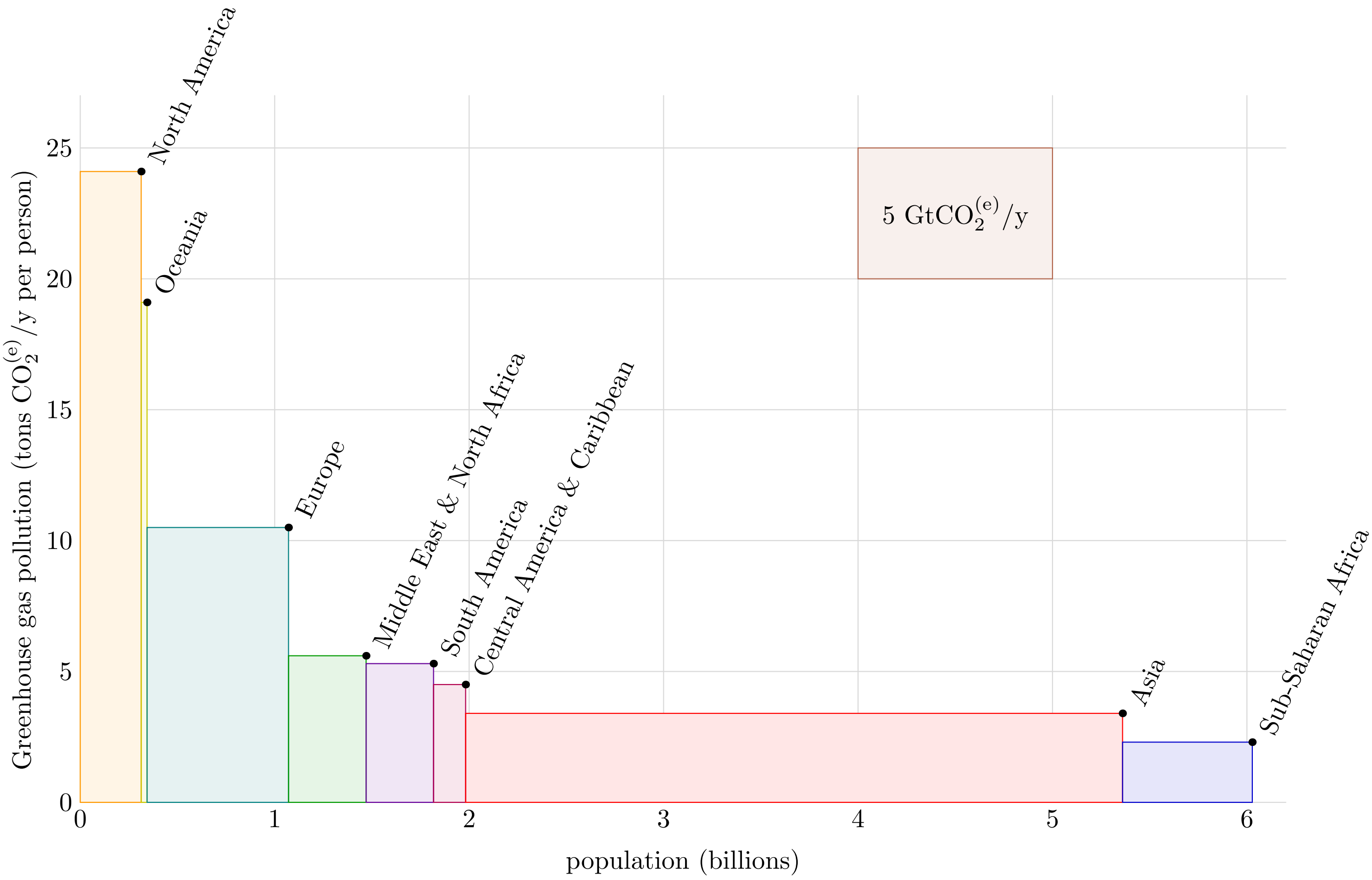


Figure 1.6. Breakdown of world greenhouse gas emissions by region.

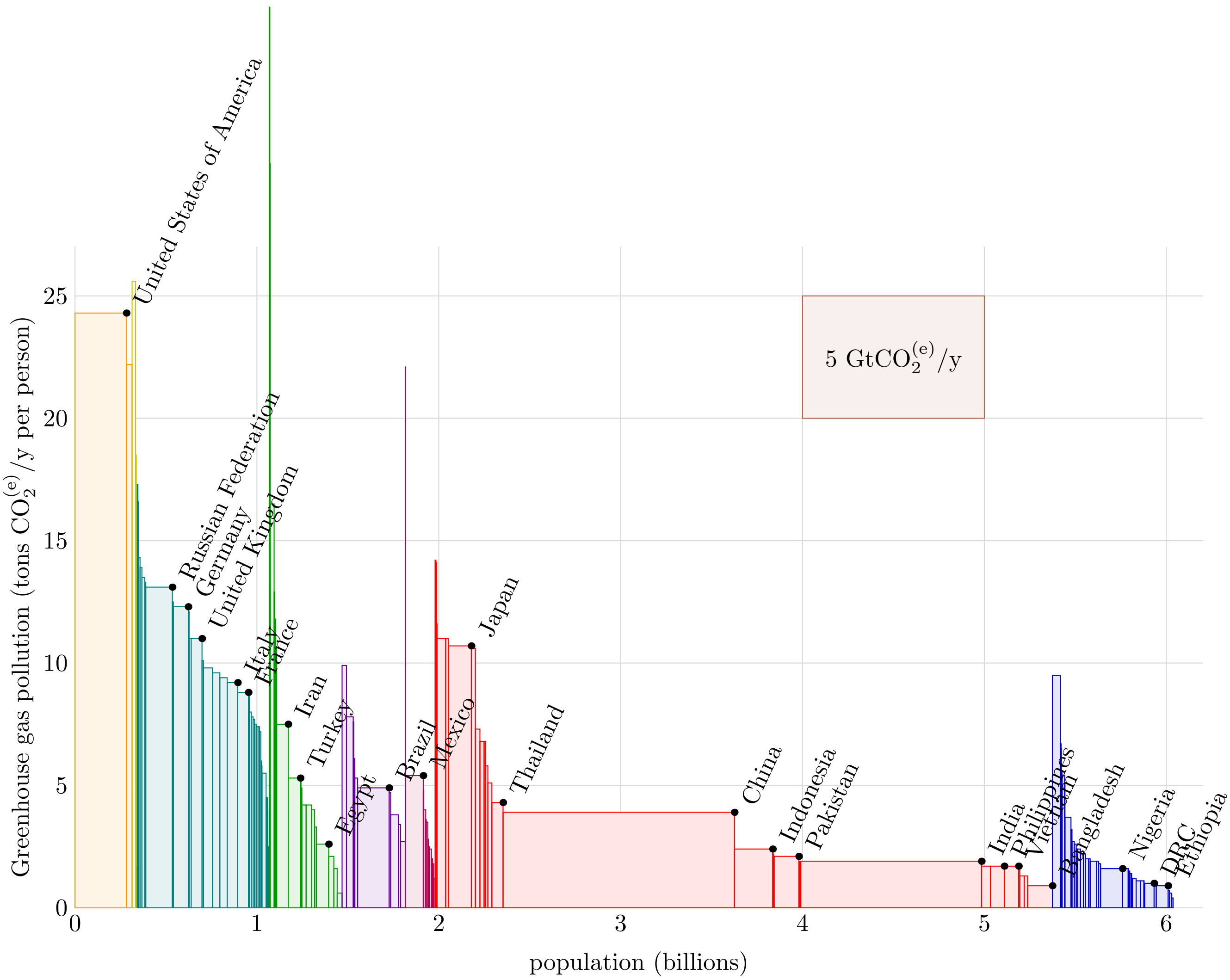


Figure 1.7. Breakdown of world greenhouse gas emissions by country.

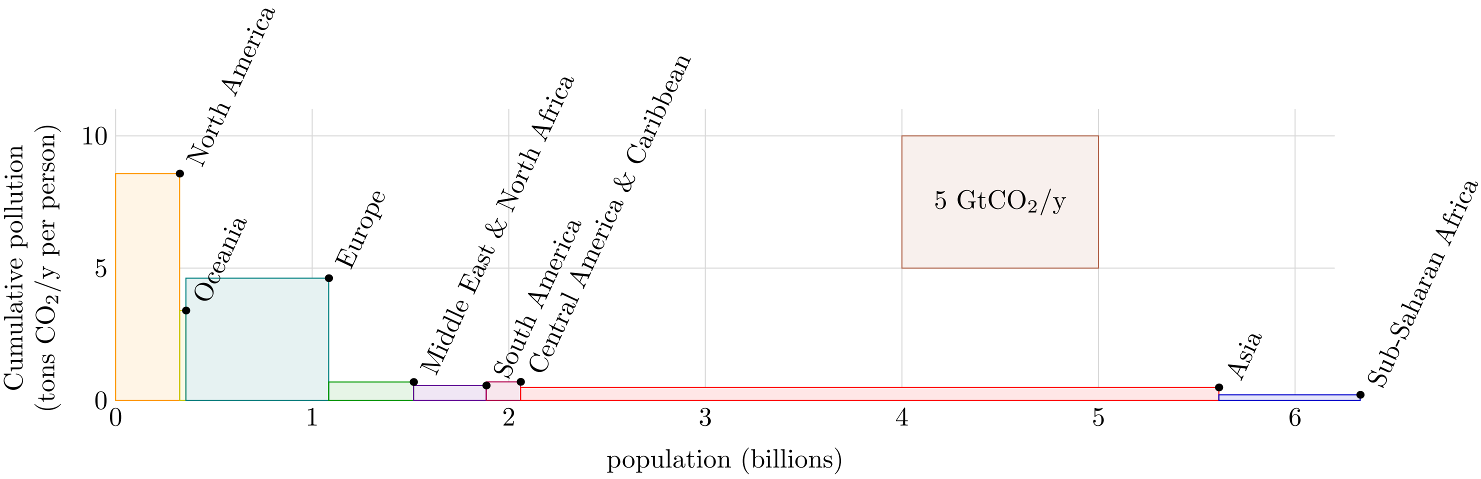


Figure 1.8. Breakdown of world CO_2 emissions by region, averaged over the period 1880–2004.

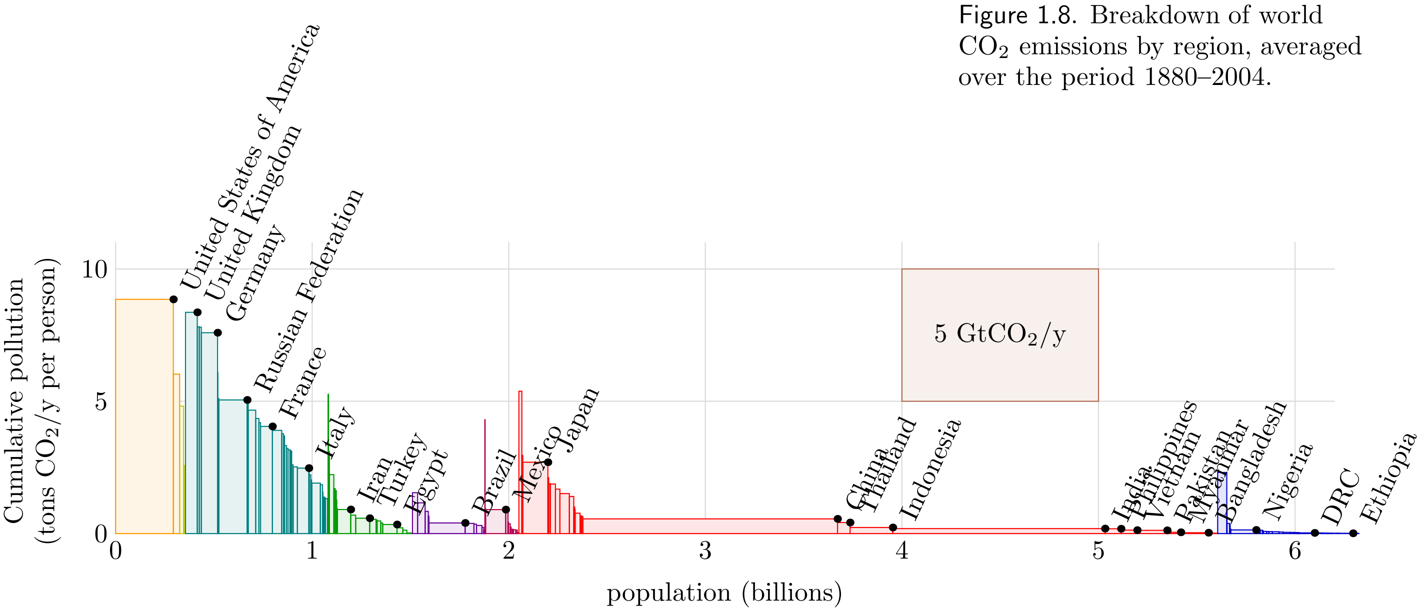


Figure 1.9. Breakdown of world CO_2 emissions by country, averaged over the period 1880–2004.

emissions are respectively 55, 37, and 30 t $CO_2^{(e)}$/y per person. The green spike contains 0.65% of the world total. The lower spike in Central America, which contains 0.1% of the world total, is made up of Antigua & Barbuda and Trinidad & Tobago, whose emissions are respectively 25 and 22 t $CO_2^{(e)}$/y per person.

Historical responsibility for climate impact

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. So if there's damage that needs rectifying, it's not so important who are the biggest emitters today; we should hold responsible the people with the biggest historical footprint. And congratulations, Britain! As figure 1.9 shows, the UK has made it onto the winners' podium. We may be only an average European country now, but in the table of historical emissions (expressed per capita), we are second only to the USA. [In absolute terms the biggest historical emitters are, in order, USA (322 Gt), Russian Federation (90 Gt), China (89 Gt), Germany (78 Gt), UK (62 Gt), Japan (43 Gt), France (30 Gt), India (25 Gt), and Canada (24 $GtCO_2$).]

Avoiding catastrophic climate change

To proceed further in our discussions of carbon, we need a rough benchmark of what we should aim for if we wish to avoid 'catastrophic' climate change. The consensus seems to be that we should aim to stay below 2°C of warming, and that this is a challenging goal. Above 2°C of warming, the probability of drastic impacts would be high; for example, the Greenland icecap would start to melt, and, over a period of another hundred years, sea-level would rise by about 7 metres. I won't recite the litany of the other bad things that would probably happen, as I am sure you've heard it before. (See [2z2xg7] if not.)

So, if we want to keep the warming below 2°C, what level of carbon pollution do we need to aim for? There is considerable uncertainty, as climate-modelling is difficult. If CO_2 levels stabilize at 550 ppm (equivalent), *all* models agree that it's likely or very likely that warming will exceed 2°C. ('Likely' means that the probability is above 2/3; 'very likely' means it's above 90%.) If CO_2 levels are stabilized at 450 ppm ('equivalent'), there's roughly a 50% chance that warming will overshoot 2°C. Only if CO_2 levels are stabilized at 400 ppm (equivalent) or below is it unlikely that warming will overshoot 2°C.

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?

Given these estimates, it seems to me that an ethical stance is to aim to stabilize CO_2 levels at 400 ppm, or, if 400 would induce enormous hardship for people today, perhaps at 450 ppm. Targets of 450 ppm, 500 ppm, and 550 ppm have been discussed by Pacala and Socolow and by the Stern review, along with estimates of the pollution rates compatible with those targets.

Stabilization wedges: Pacala and Socolow

The target adopted by Pacala and Socolow is 500 ppm (is that CO_2 only? I think so), and their paper proposes a two-step strategy to approach this target, with the current generation (2005–2055) taking responsibility for the first step, and the next generation (2055–2105) taking the second.

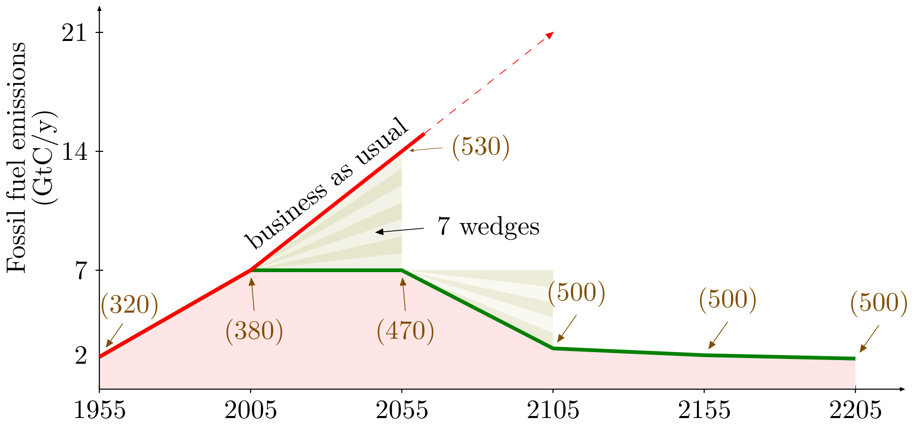


Figure 1.10. Pacala and Socolow's model of CO_2 emissions. The global emission rate is shown in billions of tons of carbon per year. The parenthetical labels show the projected CO_2 concentration each 50 years. Pacala and Socolow suggest holding emissions constant for 50 years, then decreasing emissions over the next 50 years. This strategy might stabilize CO_2 concentrations at 500 ppm.

The current generation's task is simply to keep emissions constant at 7 GtC per year (rather than let them continue, under business as usual, to 14 GtC/y). The next generation's task is to reduce emissions down to roughly 2 GtC per year. This pollution trajectory, according to Pacala and Socolow's model, would lead to stabilization at 500 ppm. (CHECK EQUIVALENT?) Pacala and Socolow chose a single baseline scenario (the ramp trajectory of figure 1.10), and it was deliberately specified as little as possible, "because we wished to keep the focus on the distinction between a world oblivious to carbon management (the baseline) and a world investing heavily in carbon management, and not to be distracted by the abundance of baselines discussed in the scenarios literature."

They introduced the notion of a 'wedge' of pollution-reduction. As shown in figure 1.10, the achievement of one wedge corresponds to avoidance of 25 Gt of carbon pollution during a 50-year period. Each generation would need to achieve roughly 7 wedges. Pacala and Socolow presented a variety of technically achievable wedges; I'll mention them in a later chapter.

What ethical targets would the adoption of the Pacala and Socolow strategy imply? Well, if their initial 7 GtC per year per planet were shared equally between 6 billion people, then we would be allowed **4.3 tonnes per year of CO_2 pollution each**. If the final target of 2 GtC per year is shared between 6 billion people, we would be allowed **1.2 tonnes of CO_2 per year each**.

I should emphasize, however, that many climate experts think that the Pacala–Socolow targets are probably not tight enough to avoid catastrophic climate change. The preferable atmospheric concentration is at most ... and in the long term, annual global emissions will need to be reduced to below 5 $GtCO_2^{(e)}$ (**1.4 GtC**). This is more than 80% below the absolute level of current annual emissions. [Stern, 2007] This target sets a useful personal benchmark: it's a bit less than

1 tonne of CO_2 each.

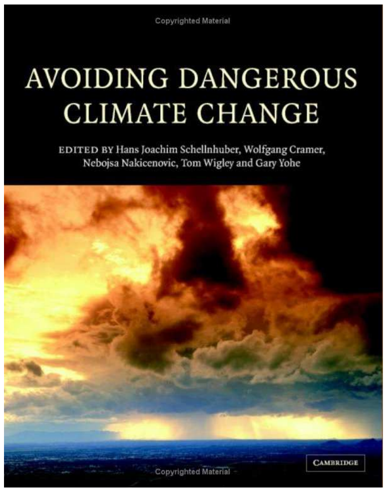


Figure 1.11. Avoiding Dangerous Climate Change © Cambridge University Press (2006). This excellent book can be downloaded from the DEFRA website.

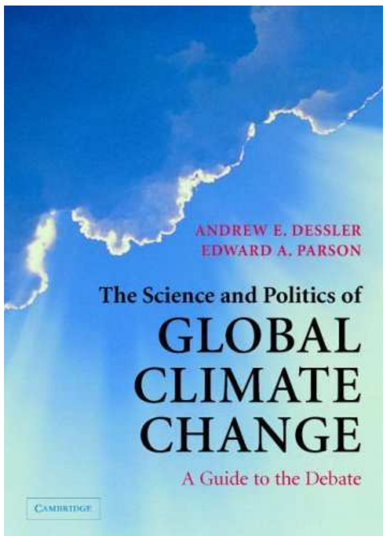


Figure 1.12. Global Climate Change © Cambridge University Press (2006).

Short-term goals for a 450 ppm target

"To stabilise at 450ppm $CO_2^{(e)}$, without overshooting, global emissions would need to peak in the next 10 years and then fall at more than 5% per year, reaching 70% below current levels by 2050."

This 2050 target, **2.1 GtC/y**, if equally shared between six billion people, corresponds to **1.3 tonnes of CO_2 per year each**. For the average Brit, who at present emits 10 or 11 tonnes of CO_2 per year, this corresponds to a reduction of nearly 90%.

Short-term goals for a 550 ppm target

Stabilising at or below 550ppm $CO_2^{(e)}$ would require global emissions to peak in the next 10–20 years, and then fall at a rate of at least 1–3% per year. By 2050, global emissions would need to be around 25% below current levels.

This 2050 target, **5.25 GtC/y**, if equally shared between 6 billion people, corresponds to **3.2 tonnes CO_2/y each**. For the average Brit, this corresponds to a 70% reduction.

And remember, the experts' advice is that stabilising at 550 ppm is a policy that almost certainly means catastrophic climate change.

> The reason Annex I [the industrialized countries] has responsibility for taking the lead in mitigation is that these are the nations which raised the level of atmospheric CO_2, bringing about the climate change problem to begin with.
>
> *Jae Edmonds*

Cumulative emissions (notes)

"modelling suggests that the 450 ppm stabilization target could be met by holding cumulative emissions to about 565 GtC while halving annual emissions by 2100, with continued reductions thereafter."

From introduction to Baer and Mastrandrea [2006] "We do not have decades in which to bend the global CO_2 curve: we have less than ten years." Simon Retallack Head of the Climate Change Team, ippr

"If at the end of the day we conclude that the challenge is simply too great, we should at the very least be honest about the risks we are incurring and imposing on others." Simon Retallack Head of the Climate Change Team, ippr

> "the 550 ppm trajectory simply can't be taken seriously, at least not as a defensible mitigation target. It poses a 78–99% risk of exceeding 2°C and a 28–71% risk of exceeding 3°C, making it difficult to maintain that arguments in favor of 550 ppm are anything more than irresponsible invitations to

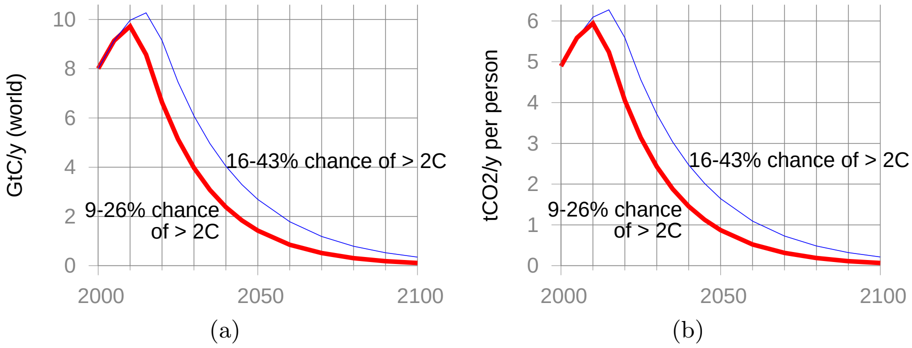


Figure 1.13. Global emissions for two scenarios considered by Baer and Mastrandrea.(a) Fossil fuel emissions expressed in GtC. (b) The same emissions, expressed in tons of CO_2 per person, using a world population of six billion. Both scenarios are believed to offer a modest chance of avoiding a 2°C temperature rise. In the lower scenario, the chance that the temperature rise will exceed 2°C is estimated to be 9–26%; the cumulative carbon emissions from 2007 onwards are 309 GtC; CO_2 concentrations reach a peak of 410 ppm, $CO_2^{(e)}$ concentrations peak at 421 ppm, and in 2100 CO_2 concentrations fall back to 355 ppm. In the upper scenario, the chance of exceeding 2°C is estimated to be 16–43%; the cumulative carbon emissions from 2007 onwards are 415 GtC; CO_2 concentrations reach a peak of 425 ppm, $CO_2^{(e)}$ concentrations peak at 435 ppm, and in 2100 CO_2 concentrations fall back to 380 ppm.

catastrophe. ” “So we stabilize at or below 450, or ruin the planet for hundreds if not thousands of years.”

“Unfortunately, “realistic” men and women are still advocating targets in this neighborhood of 550 ppm. Even the UK’s much praised Stern review of the economics of climate change does so, though in a manner so circumspect that its authors seem ashamed of their own fatalism.” *Tom Athanasiou, www.fpif.org*

Avoiding 2°C

When I started writing this book, climate change was in the news, but I didn’t hear the climate scientists saying the sort of things they are saying now. The urgency with which rapid action is recommended has increased. Two years ago, people talked of capping emissions near 1990 levels for a few decades, or reducing emissions by 60% by 2050. But now there seems robust agreement that to have a good chance of avoiding a dangerous rise in global temperatures, we have to cut global emissions by more, and sooner.

Figure 1.13 shows two emissions scenarios studied 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%.

Given that a 2°C rise is widely viewed as being highly undesirable, it seems to me that society should be focussing all its attention on goals similar to these scenarios. It must be emphasised that, whereas the Stern review mentioned the idea of stabilizing $CO_2^{(e)}$ concentrations at 450, 500, or 550 ppm, with most of Stern’s analysis focussing on 500 or 550 ppm, the highest $CO_2^{(e)}$ concentration contemplated by Baer and Mastrandrea's scenarios is about 440 ppm, and the longer-term concentrations they suggest are required are all below 410 ppm.

Climate experts agree that the total amount of CO_2 emitted is the important quantity. Let's assume we accept Baer and Mastrandrea's judgement that the total amount emitted for the century from 2007 onwards must be at most 400 GtC. Then if we delay putting their plan into action by ten years – during which global emissions bobble up to 10 GtC per year – then we will have blown of one quarter of our remaining carbon budget during just those ten years.

How does this budget (300–400 Gt carbon) compare with estimates of easily accessible oil and gas remaining? World oil reserves: 1.2–2.9 trillion barrels, depending to whom one talks. Assuming 110 kg of carbon per barrel, that's 130–320 GtC. Wikipedia says world natural gas proven reserves are 170 000 billion m^3, which, at 0.5 kg carbon per m^3, is about 85 GtC. So the total of oil and gas reserves is about 200–400 GtC

So assuming that we should limit our total cumulative emissions to 400 GtC, it's a good approximation to say that we could burn all the oil and all the gas, as long as we don't emit a single carbon atom from any of the coal.

Finally, how does this budget of 300–400 Gt carbon compare with what we've already emitted? From 1880 to 2004, cumulative emissions of carbon have totalled 297 GtC. [The biggest historical emitters are USA (88 GtC), Russian Federation (25 GtC), China (24 GtC), Germany (21 GtC), UK (17 GtC), Japan (12 GtC), France (8 GtC), India (7 GtC), and Canada (6.5 GtC).] So this announcement of a carbon budget comes balanced roughly at the half-way point of the overall total.

Moving on

We need to summarise these figures in a single number. The Stern review focuses on the goal of stabilising at 500–550 ppm $CO_2^{(e)}$. I'm not sure why. According to the consensus described by Stern, this goal would give a high probability of temperature rises *exceeding* 2°C. It seems to me that 450 ppm $CO_2^{(e)}$ is the right goal. The Conservative Party's Quality of Life Policy Group agrees that Stern's emissions target is 'too complacent'.

You can take your pick, but I suggest an ethical target is at most about **2 GtC/y** of pollution per planet. This rate of emissions into the atmosphere would balance the current rate of absorbtion by the oceans (figure 1.14). However, I'd say that even this target is not self-evidently safe, fair, and ethical: the surface waters of the oceans are becoming steadily more acidic, and continued pollution rates of 2 GtC/y would ensure that this acidification would continue. So if you care about coral reefs, maybe the ethical target is even smaller than 2 GtC/y.

2 GtC/y of pollution per planet corresponds to **1.2 tons of CO_2 per year each**, if shared equally among everyone on the planet. For the average Brit, who at present emits 10 or 11 tonnes of CO_2 per year, this corresponds to a 90% reduction. Even if one were to judge that an unequal sharing of pollution is appropriate, a huge reduction is still required by Brits: for example, if one said that the richest two billion people get equal pollution rights, and the other four billion get *none*, rich Brits would then have a pollution allowance of 3.6 tons of CO_2 per year each, which is still a 67% reduction on the current UK average. So even the most extreme ethical position (in terms of generosity to wealthy countries) leads to a requirement to reduce emissions by about 70% as soon as possible. When thinking about the allocation of pollution rights, don't forget that we rich countries (Europe, North America, and Australia) are responsible for 90% of the cumulative emissions so far; and it's the cumulative total emissions that matter, that cause global warming – not the rate.

The reduction required in the UK's CO_2 emissions is thus so great that it's a fair approximation to say we must aim to entirely cut out *all* uses of fossil fuels that release greenhouse gases. If we aim for a 100% reduction, maybe we'll have a chance of hitting 90%. This goal, of becoming a zero-carbon country, leads to actions radically different from those that our government has so far taken. If all we want is a 5% reduction here or a 10% reduction there, then switching from old fossil-fuel power stations to new is grand; more efficient fossil-fuel-powered cars are grand; new gas pipelines, to replace coal supplies, are grand; decentralized gas power stations are grand. All these sort of changes may, if done well, give 10% reductions in greenhouse gas emissions. But

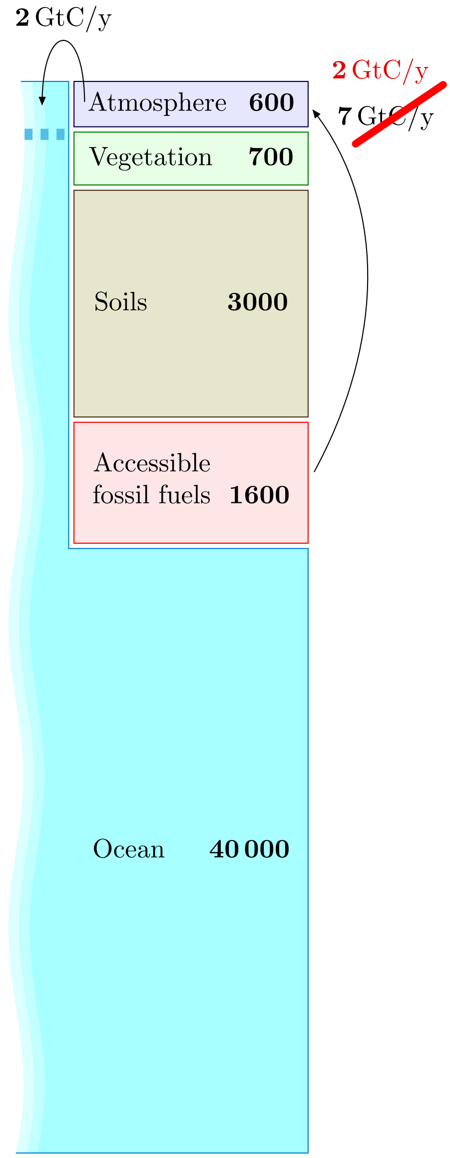


Figure 1.14. What we need to do to stabilize the CO_2 concentration in the atmosphere. Global emissions must be reduced to about 2 GtC per year. (This might not be a sufficient reduction to prevent pollution of the surface waters of the ocean.)

they don't get us off fossil fuels. If our goal is 90% reductions in CO_2 emissions, such tweaking of the fossil-fuel-based energy supply may do more harm than good, since we'd be investing today's money in new fossil-fuel power systems which we'll then be stuck with for decades.

Energy exchange

How do our energy estimates, in kWh per day, translate into carbon pollution? Well, it depends on whether fossil fuels are involved, and which fossil fuels; and it depends whether the fossil fuels are being used for heat or electricity. As a ballpark figure, 10 kWh per day is equivalent to 1 ton of CO_2 per year. Tables 1.15 and 1.16 give more detailed figures. Some uncertainty in the figure for natural gas stems from the possibility of gas leaks along the way from the hole in the ground to the place where the gas is burned. Accidental methane pollution has nearly eight times as big a global-warming effect as equivalent CO_2 pollution arising from burning the methane; so if say 5% of the gas leaks from pipelines on the way from Russia to England, the equivalent CO_2 pollution is boosted by 40%.

	CO_2	Exchange rate
Diesel	250 g CO_2/kWh	10 kWh/d ↔ 0.9 tCO_2/y
Biodiesel	320 g CO_2/kWh	10 kWh/d ↔ 1.2 tCO_2/y
Gas	200 g CO_2/kWh	10 kWh/d ↔ 0.7 tCO_2/y

Table 1.15. Exchange rates between carbon pollution and chemical energy. The biodiesel figure does not include the carbon cost of making the biodiesel.

	CO_2	Exchange rate
Coal	1000 g CO_2/kWh(e)	10 kWh/d ↔ 3.6 tCO_2/y
Gas	400–500 g CO_2/kWh(e)	10 kWh/d ↔ 1.6 tCO_2/y
Nuclear	16–30 g CO_2/kWh(e)*	10 kWh/d ↔ 0.06–0.1 tCO_2/y

Table 1.16. Exchange rates between carbon emissions and electrical energy.
(∗) The figure for nuclear depends on the source of the energy for nuclear fuel mining and processing. Currently, the UK is highly dependent on fossil-fired electricity generation, making indirect emissions the primary source of nuclear CO_2 output. If nuclear plants replaced fossil-fired plants as the primary electricity generators, the CO_2 emissions for nuclear power would fall. (from Nuclear-paper2, Sustainable Development Commission p23)

Consensus on target level

Stern review page xvii (17) executive summary.

(see also stern.tex)

"The current evidence suggests aiming for stabilisation somewhere within the range 450–550 ppm $CO_2^{(e)}$. Anything higher would substantially increase the risks of very harmful impacts."

"Uncertainty is an argument for a more, not less, demanding goal, because of the size of the adverse climate-change impacts in the worst-case scenarios."

"Three elements of policy for mitigation are essential: a carbon price, technology policy, and the removal of barriers to behavioural change.

Leaving out any one of these elements will significantly increase the costs of action."

Sea level

If all of Greenland icecap melts then global sea level rises by 7 metres. (Plan B, Science ref)

Over the 20th Century it averaged 1.7mm per year.

If the acceleration continues at the current rate, the scientists warn that sea levels could rise during this century by between 28 and 34cm.

http://news.bbc.co.uk/1/low/sci/tech/4651876.stm

Area of Greenland icecap / Area of oceans = 1 834 000 km^2 / 360 000 000 km^2 = 1/2%. If the average thickness of the icecap is 2 km, and if it all gets spread over the oceans, the depth will be 1/2% of 2000 m, which is 10 m. And experts seem to agree that a global temperature rise of more than 2°C would cause the Greenland icecap to melt. (And from page 3 of part 2 of Stern review, the estimated eventual sea-level rise is 7 m.)

The possible collapse of the West Antarctic Ice Sheet is also believed to be a cause for concern; the scientific community has yet to reach consensus on estimates of the critical threshold temperature above which the collapse would be significant.

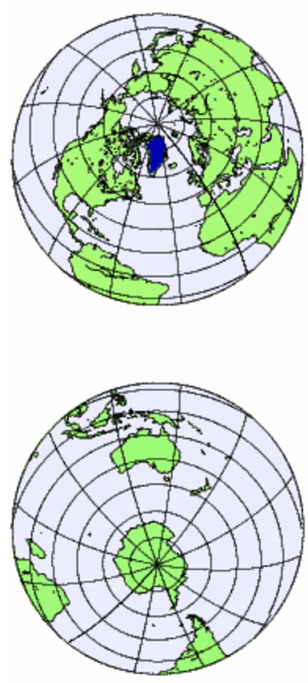


Figure 1.17. The Greenland icecap's area (top centre) is 1/200 of the area of the oceans. (Equal area azimuthal projections.)

Mythconceptions

People say a lot of things about climate change. Which of the following statements are true?

'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 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.' (Adapted from Dominic Lawson's column in the *Independent*, Friday 8 June 2007.)

A mix of *True*, *Misleading*, and *False*.

Yes, natural flows of CO_2 *are* much larger than the additional flow we switched on one 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 key fact is that the 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 left

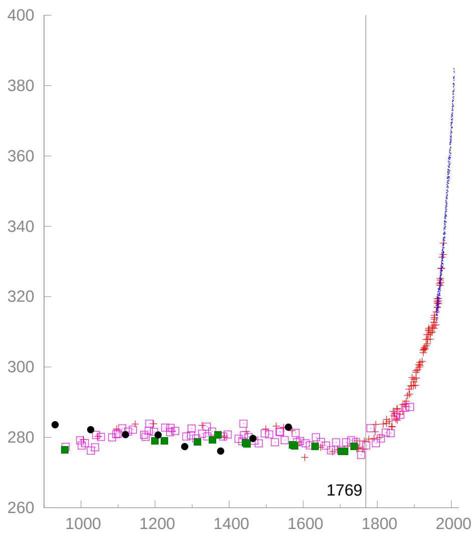


Figure 1.18. It's the sun wot done it?! CO_2 concentrations (in parts per million) for the last 1100 years, measured from air trapped in ice cores (up to 1977) and directly in Hawaii (from 1958 onwards). Some 'sceptics' have asserted that the recent increase in CO_2 concentration is a natural phenomenon caused by solar activity. Does 'sceptic' mean 'a person who has not even glanced at the data'? Just look: from 900 AD to 1700 AD, CO_2 concentrations never strayed outside the range 280 ± 10 ppm. In 2004, the CO_2 concentration reached 377 ppm. Do you think, perhaps, something unnatural happened between 1800 AD and 2000 AD? How can *anyone* look at this graph and, with a straight face, say that it's a natural variation?

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.

There's a second issue here. Some people emphasize that 'never-ending variations in climate are natural,' presumably implying that we should, for example, view the recent unusually hot years as natural rather than man-made events. Yes, lots of other factors cause ups and downs in temperature. We can't attribute particular storms or summers completely to human-induced climate change. But this complexity of the climate doesn't mean that mankind's activities can't make a difference! Indeed I think it is unnecessary for climate-change activists to make 'we have already changed the climate' a plank of the argument. Sceptics or troublemakers could always argue that what's happened recently is a fluke of some sort, and then you end up arguing about the past. There's little point in arguing about the past when we have concrete facts about the future.

There is strong scientific agreement that gung-ho fossil-fuel-burning *will* make a difference. *Exactly* what difference, no-one knows. The climate is a complex beast. But this much is agreed:

1. Extra carbon dioxide in the atmosphere leads to extra carbon dioxide in the surface waters of the oceans, which causes acidification; under another hundred years of 'business as usual', this surface acidification would cause significant changes in ocean life.

2. Burning fossil fuels thickens the earth's duvet. CO_2 is a greenhouse gas, and extra carbon dioxide in the atmosphere enhances the greenhouse effect. A doubling of atmospheric CO_2 concentration

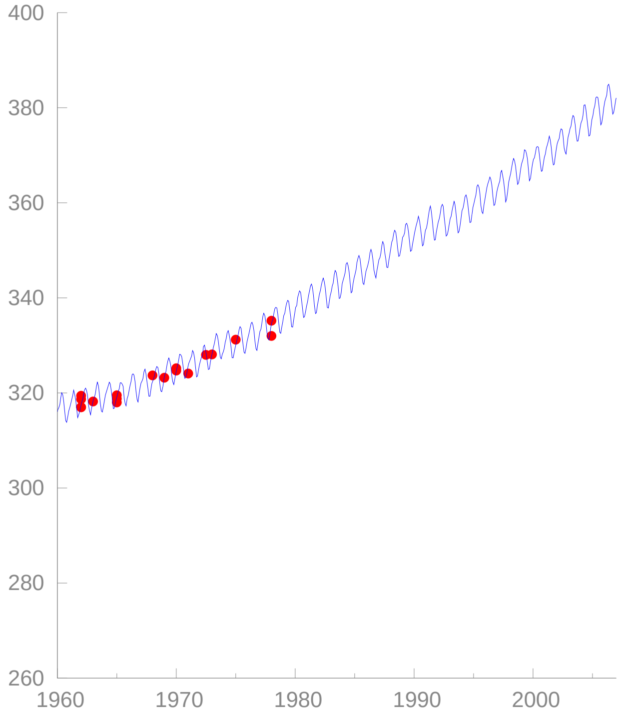


Figure 1.19. Natural influences on CO_2 can be bigger than man-made influences. This detail from figure 1.18 confirms this assertion, in the sense that the natural annual variations are bigger (over one year) than the steady man-made increase (over one year).

(which is where we're heading within another century of 'business as usual') would almost certainly cause a rise in average global temperatures. (Exactly how big a rise, no-one knows; there's a lot of uncertainty about this sensitivity of the climate to CO_2. But the best models currently available all suggest that rises of at least a couple of degrees Celsius are likely.)

'In the past six years, the Thames Barrier, built to defend London from flooding, has been raised a staggering 56 times, compared with just three times in first six years after in was built in the 1980s.' (Green Party). 'Use of the Thames Barrier has increased sharply: between 1986 and 1996 the Thames Barrier was raised 27 times and between 1996 and 2006 it was raised 66 times.' (Liberal Democrat party.)

True. The upper histogram in figure 1 shows the total number of closures of the Thames barrier by year. The winters of 2000–1 and 2002–3 were especially busy times! However, if you're after an indicator of UK climate change, DEFRA recommends that it's better to count only the number of closures of the barrier to prevent flooding by tidal surges. (The barrier is also raised to prevent flooding from the combination of excess river water with normal high tides, and sometimes just to retain water in the river.) This DEFRA advice has been used to attack people like Al Gore who have mentioned the increasing number of barrier closures as evidence of sea-level rise. But such attacks are unfair. The number of tidal-surge closures per year is shown in the lower histogram.

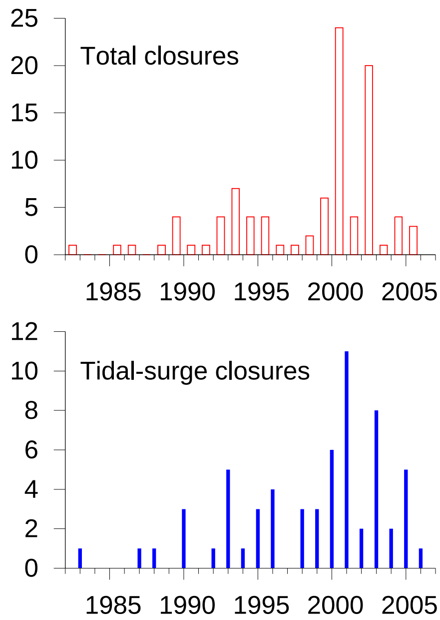


Figure 1.20. Thames Barrier closures, 1983 to 2006. Sources: Environment Agency `http://www.environment-agency.gov.uk/` and Hansard [yp5s6p].

There were 34 closures against tidal surges in 2000–5, and only 3 in 1983–1988. In 1996–2005 inclusive, there were 44 closures against tidal surges, and in 1986–1995 inclusive, there were 15. So the corrected data show just the same trends. These facts do not necessarily prove anything about global sea-level rise, but they're certainly worth your attention if you are one of the 750 000 Londoners at risk from a storm surge.

"Nuclear power is bad because it releases extra energy into the environment, thus increasing global warming."

False.

The sun delivers a power of about 120 000 TW to the earth, heating up the ocean, ground, and air. All the world's nuclear reactors add an extra 1 TW to this.

"Walking to the shops 'damages planet more than going by car'"; "Walking does more than driving to cause global warming, a leading environmentalist has calculated." [yta3ut]

There is a bit of truth lurking in this statement, and a lot of distortion.

Here's the statements made by Chris Goodall. 1. Driving a typical UK car for 3 miles [4.8km] emits about 0.9 kg of CO_2 pollution. [Check this agrees with chapter **??**.] 2. Walking instead would use about 180 calories. [Check this agrees with chapter **??**.] 3. To get 180 calories from beef requires 100 g of beef, which emits about 3.6 kg of CO_2. [Check this agrees with chapter **??**.]

I view all three of these statements as roughly true. But there are two niggles. First, the calculation assumes that someone who walks gets *all* their energy from eating beef. Second, I think that it's poor journalism to summarise these sums by saying 'walking is worse than driving'. I think it would be better to say 'a beef-heavy diet could easily contribute about a quarter of your carbon footprint'.

'Warming is caused by the burning of fossil fuels. So isn't carbon sequestration at power stations missing the point – surely we should stop liberating the energy in the first place?'

It's true that every fossil-fuel-burning car provides the community with a 60 kW heater – thus congested cities may be significantly warmer thanks to their cars; buildings and power stations also emit heat into their surroundings. But it is an error to imagine that the *heat* from fossil-fuel burning is making any significant contribution to global warming.

No. Warming is caused by the *sun*, not by fossil-fuel energy.

Here's how the numbers work: the average solar energy hitting the earth, per square metre, is 250 W/m^2 per day, which is 6 kWh/m^2 per day. The area of planet per person is 90 000 m^2. So the total incoming solar power is 500 000 kWh per day per person. Even an affluent person's fossil fuel power emissions, at 500 kWh per person per day, would contribute only an additional one thousandth. The *average* human's fossil-fuel power emissions, at 25 kWh per day per person, are twenty times smaller again.

The sun causes global heating. Greenhouse gases in the atmosphere cause the equilibrium temperature to increase by making it a little harder for the solar-heated ocean and ground to radiate the sun's heat back out into the cold of outer space.

'Global warming is a green hoax: the oceans have a huge heat capacity, so the atmosphere will take ages to warm up the oceans'.

False. This statement, taken from an entertaining and thought-provoking book called 'Green Hoax Effect', misunderstands the way heating works. The oceans don't get indirectly heated by the warm touch of balmy *air* on their surface: the oceans are heated directly by the *sun*, and then pass on this heat by radiation, evaporation, and conduction, to the air above. Yes, the oceans have a big heat capacity. But the sun is a big and direct heater.

'Volcanos emit more CO_2 than humans.'

False. Sometimes, volcanos do emit lots of CO_2, and the climate is drastically affected. But the last time this happened was 65 million years ago, at the K-T boundary; and these eruptions were on a scale quite unlike anything humans have ever seen. Enormous lava flows in India called the Deccan traps are the calling card of a mega-eruption that pumped out collosal quantities of CO_2 and other gunk, transforming the climate and leading to the extinction of most dinosaurs. (Cite Darwin Lecture series.)

Current vulcanism, on average, emits less than 0.1 GtC per year.

'There's no point in my reducing my fossil fuel consumption – someone else will just burn my fossil fuels a bit later'.

There may be some truth in this: your fossil-fuel sales organization might have bought oil at a good price by guaranteeing to purchase a particular quantity over one year; if you stop buying from them, they will respond by lowering the price slightly until someone else buys up your share; and maybe that someone-else wouldn't have consumed in that way, if the price had not fallen. In this scenario, your reduction in consumption leads to a slight fall in oil company profits, but little change in global emissions. However, even if everyone reduced their consumption of fossil fuels, we still have the question: 'does this really make a difference? – if the fossil fuels get burned over a longer period, isn't that just as bad?' The answer to this question is in section 1 (p.5). Emitted CO_2 doesn't just go and sit in the atmosphere forever. It *is* better to burn fossil fuels slowly rather than fast, because the oceans slowly absorb CO_2 from the atmosphere. A slow trickle of CO_2 emissions causes lesser climate change. [But Jon Gibbins says 'it's a good approximation to say that it's just the total amount that matters'. Need to make a clearer account of this issue.]

Targets

The government's target for a 60% reduction in carbon pollution by 2050 has been criticised by an all-party group of MPs and peers for not being a sufficiently tough target, and for failing to include international aviation and shipping http://news.bbc.co.uk/1/low/uk_politics/6928084.stm.

David Miliband: binding carbon targets are 'silly' http://politics.guardian.co.uk/green/story/0,,1947588,00.html

Notes

4 CLIMATE CHANGE ... WAS A CONTROVERSIAL QUESTION. Indeed there still is a 'yawning gap between mainstream opinion on climate change among the educated elites of Europe and America' [voxbz].

7 WHERE IS THE CARBON? Sources: Schellnhuber et al. [2006] Davidson and Janssens [2006].

7 THE RATE OF FOSSIL FUEL BURNING... Source: Marland et al. [2006].

8 RADIOACTIVE CARBON ... HAS PENETRATED TO A DEPTH OF ONLY ABOUT 400 M. The mean value of the penetration depth of bomb ^{14}C for all observational sites during the late 1970s is 390 ± 39 m (Broecker et al., 1995). From [3e28ed]

7 RECENT RESEARCH INDICATES CARBON-UPTAKE BY THE OCEANS MAY BE REDUCING. http://www.timesonline.co.uk/tol/news/uk/science/article1805870.ece, http://www.sciencemag.org/cgi/content/abstract/1136188, [yofchc], Le Quéré et al. [2007].

5 CARBON DIOXIDE IS A GREENHOUSE GAS. For an accessible explanation of this fact, see 'The CO_2 problem in 6 easy steps' [34pj5e]. Some key steps from the explanation: a doubling in CO_2 is estimated to increase the 'forcing' by about 4 W/m^2. 'Forcing' is the strange name used to describe the warming effect of greenhouse gases. The total forcing of all the natural greenhouse substances is about 150 W/m^2. An increase of 4 W/m^2 is roughly equivalent to a 2% increase in the intensity of the incoming sunlight.

14 PACALA AND SOCOLOW Socolow [2006].

14 MANY CLIMATE EXPERTS THINK THAT THE PACALA–SOCOLOW TARGETS ARE PROBABLY NOT TIGHT ENOUGH TO AVOID CATASTROPHIC CLIMATE CHANGE. 'What is required to reduce the risk of the global temperature rising above 2°C is at least a 60% reduction of CO_2 emissions by 2050 against 2000 levels.' Barnaby and Kemp [2007].
From Stern [2007]: Even the radical pollution trajectory suggested by Socolow takes the climate to places we've never been before. "If annual emissions were to remain at today's levels, greenhouse gas levels would reach close to 550 ppm $CO_2^{(e)}$ by 2050. ... this would commit the world to a warming of around 2–5C. Positive feedbacks, such as methane emissions from permafrost, could drive temperatures even higher. Near the middle of this range of warming (around 2–3C above today), the Earth would reach a temperature not seen since the middle Pliocene around 3 million years ago. This level of warming on a global scale is far outside the experience of human civilisation."

18 THE CONSERVATIVE PARTY'S QUALITY OF LIFE POLICY GROUP: *Blueprint for a Green Economy* – Submission to the Shadow Cabinet. Chairman, Rt Hon John Gummer MP; Vice-Chairman, Zac Goldsmith (September 2007) [27j2u2]. "It is our judgement that the stabilisation target range for CO_2 equivalent should be 400ppm–450ppm."

19 ACCIDENTAL METHANE POLLUTION HAS EIGHT TIMES AS BIG A GLOBAL-WARMING EFFECT... I say eight times, not the standard '23 times', because '23 times' is the warming ratio between equal *masses* of methane and CO_2. each ton of CH_4 turns into 2.75 tons of CO_2 if burned; if it leaks, it's equivalent to 23 tons of CO_2. And 23/2.75 is 8.4, which is near enough eight.
The standard '23 times' is the 'global warming potential$_{100}$' of methane. This quantity has a subjective definition, because it depends on a choice of timescale for concern about global warming. The global warming potential of a gas is defined to be the amount (mass) of CO_2 which would have to be released in order to have an *equal impact* on the atmosphere as a unit mass of the gas. [Emphasis added.] This definition might sound objective, but we have to define what we mean by 'equal', when in fact we are comparing gases with different effects. Methane, for example, is a stronger absorber of infra-red radiation than CO_2, but it lasts only a few years in the atmosphere before it is changed into another chemical (most likely CO_2).
The lifetime of methane in atmosphere (before it turns to CO_2) is about 12 years. Its global warming potentials on time horizons of 20 years, 100 years, and 500 years are respectively: 62, 23, and 7.
[Trees do not produce methane; don't believe everything you read in *Nature*.]

21 Figures 1.18 and 1.19. The data are collated from Keeling and Whorf [2005] (measurements spanning 1958–2004); Neftel et al. [1994] (1734–1983); Etheridge et al. [1998] (1000–1978); and Siegenthaler et al. [2005] (950–1888 AD); and Indermuhle et al. [1999] (from 11 000 to 450 years before present).

THAMES BARRIER. Quotes from `http://www.greenparty.org.uk/news/2890`, `http://www.libdems.org.uk/environment/issues/stern.html`.

In a later chapter we'll discuss another exchange rate involving CO_2, namely the energetic cost of recapturing CO_2 after people made the mistake of burning fossil fuels.

`http://www.defra.gov.uk/environment/statistics/globatmos/gaemunece.htm`

`http://www.defra.gov.uk/environment/statistics/globatmos/gagginvent.htm`

nice graph of UK CO2 emissions.

The total (tonnes carbon equivalent) was about 160 MtC/y of which most is in the energy industries (about 70) and about equal amounts in road, residential and "other" (25 each)

The sustainability goal proposed by Scientific Council of the German Government for Global Environmental Change (WBGU) (Wissenschaftlicher Beirat für Globale Umweltveränderungen) is emitting not more than 1 ton of carbon dioxide per capita by 2050 to avoid drastic climate change.

Non-energy contributors to greenhouse gas pollution

Carbon pollution is mostly (98.5 percent) associated with the combustion of fossil fuels – coal, natural gas, and petroleum; but a small percentage of the carbon pollution – less than 5% – is associated with cement making and other industrial and chemical processes.

Cement

Cement production accounts for roughly 1/4 Gt C/y, compared with roughly 7 Gt C/y pollution from burning fossil fuels.

The conversion factor is 0.138 tons of carbon per ton of clinker produced. The United States produced 65 million tons of cement clinker in 1993, which implies carbon emissions of nearly 9 million tons – about 0.1 tons CO_2 per year per person.

[y76zpr]

Other non-fossil fuel production of CO_2

Lime is used in agriculture, construction, steelmaking, pulp and paper manufacturing, and water purification. Lime is manufactured by heating either limestone or dolomite ($CaMg(CO_2)_3$), which releases carbon dioxide. In the USA in 1993, 17 million tons of lime were produced. This corresponds to roughly 0.04 tonnes of CO_2 pollution per year per person.

Soda ash is an alkali used for making glass and chemicals, including baking soda. The production and use of soda ash in the USA released about 0.02 tonnes of CO_2 pollution per year per person.

Aluminium production creates carbon pollution, because carbon anodes are burned up during the electrolysis. Roughly 2 tons of carbon dioxide are emitted for each ton of aluminum produced. The USA produced about 4 million tons of aluminium in 1992, releasing roughly 0.03 tonnes of CO_2 pollution per year per person.

Notes

This is a good ref to point to on how ocean currents work. [2pfr9g]

Complexity of climate / temperature / CO_2 relationship

Vostok ice core data.

Source: Petit June 1999 Nature.

The current interglacial is called the Holocene.

The previous interglacial period (about 100 000 y ago?) was called the Eemian, and its peak temperature was 2 C higher than the peak temperature so far of the Holocene. At that time, sea level was 5 m higher.

Data

The main effect of increased CO_2 in the atmosphere is on emissions in the 13 and 19 micrometres range.

Royal Society [2007]

Do offsets make things better or worse?

To put it another way, 'does buying offsets make people more or less determined to cut their own carbon footprint?'

I think it's likely the answer is 'less' – "vroom vroom! It's OK for me to zoom around by car and plane because I've bought an (unreasonably cheap, and probably not genuine) 'offset'".

Final footprint

Hindu cremations use up to 600 kg of firewood; a typical cremation releases 0.8 t CO_2. Source: The Hindu 15/5/2007.

Notes

Total estimated fossil fuels are estimated at 1,643 GtC.

Reference in s.bib, Izrael article in CUP book.

Total amount of C used to be 41,000 Gt. Atmosphere contained 600 Gt.

Chapter 14 says that forests function as a carbon sink of approx 1.2 Pg C per year.

(Pg is a billion tonnes of C)

The 3Pg figure is mentioned in ch41 also.

History of CO_2 pollution

At the peak of UK coal consumption, the per-capita emissions of CO_2 were 18 tons per year.

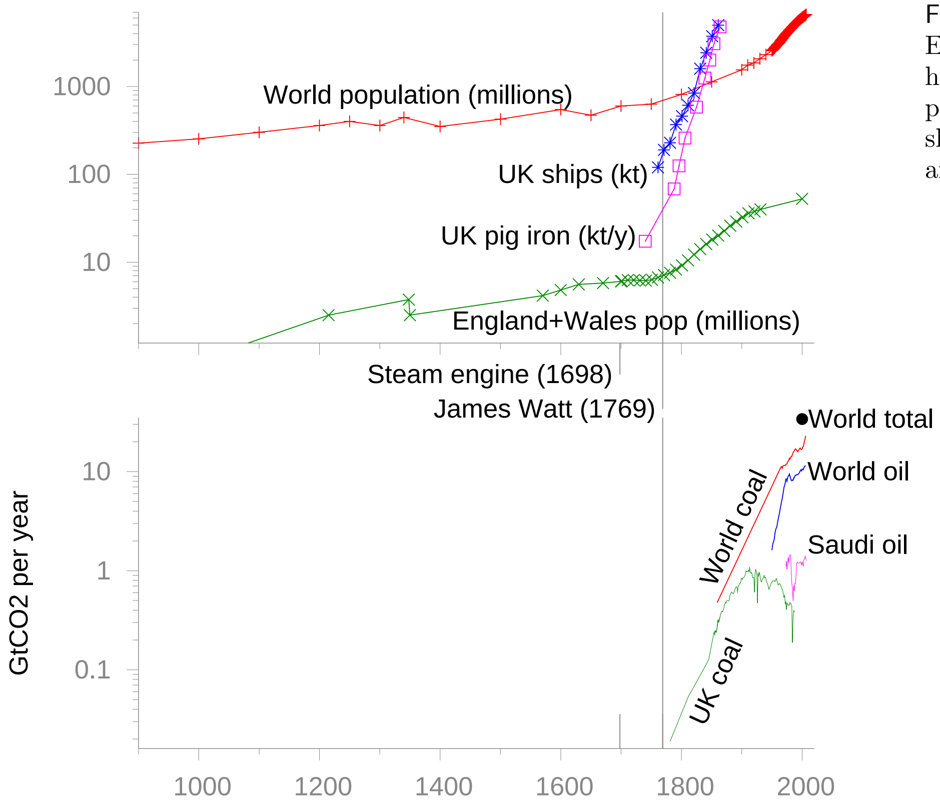


Figure 1.21. Population of England, and the world; and history of UK coal production, pig-iron production, number of ships; also Saudi oil production and world coal and oil production.

2

Methane, concrete, cows, and mythconceptions

A possible chapter collating all the important non-CO_2 greenhouse gases, and all the important non-fossil-fuel sources of greenhouse gases.

Mythconceptions

"Methane from cows is a bigger contributor to climate change than fossil-fuel burning."

False. Although indeed cow-burp methane *is* a significant contributor to global warming, it's not as big as CO_2. The world's 1.3 billion cows annually produce nearly 100 million tons of methane. The standard view is that one ton of methane is equivalent to 23 tons of CO_2. [Here's a rough story for where this '23' comes from. To estimate the impact of a methane molecule, we need to know two things: how effective it is at absorbing radiation, and how long it's expected to stay in the atmosphere. Molecule for molecule, methane is 25 times as greenhouse-effective as CO_2. Methane has a lifetime of 12 years in the atmosphere. Which is maybe 3 times shorter than CO_2. And each ton of methane contains 2.75 times as many molecules as a ton of CO_2. So overall, per ton, methane is about $25/3 \times 2.75 \simeq 23$ times as bad as CO_2.] So the methane emissions are roughly equivalent to 2.3 tons of CO_2, or 0.6 Gt of Carbon.

Total carbon emissions from fossil fuels are about 7 Gt of Carbon, in the form of CO_2. So cow-burp methane is contributing about 8% as much global warming as CO_2 pollution.

The standard view (one ton of methane is equivalent to 23 tons of CO_2) is criticised by some experts because it's derived on the assumption that what we care about is 'total global warming impact over a one hundred-year period'. If we decide that are concern is 'global warming impact over twenty years' instead, then the relative impact of methane is larger, and reducing methane pollution is a higher priority. In sum, methane and CO_2 are both bad; methane is especially bad for the next ten years after you let it go; CO_2 is bad for a long time. Methane turns into CO_2 on a ten-year timescale, so it turns from 'especially bad' to just 'bad' for a long time.

While we're talking about significant environmental impacts of agriculture, we should note that a climate-change impact even bigger than that of cow-burp methane is delivered by fertilizers. Fertilizers not only have an energy cost, as fossil fuels are used to make them; nitrogen-based fertilizers end up releasing nitrous oxide (which is a greenhouse gas). The net impact is [GET FIGURE FROM STERN REVIEW] $CO_2^{(e)}$.

'Burning hydrocarbons damages the ozone layer'.

Might be true, but irrelevant. Some people seem to mix up 'climate change' (global warming) and 'ozone layer depletion', as if they are a single issue. The consensus on 'why we should massively reduce fossil-fuel-burning' is that the CO_2 emitted increases global warming. The ozone layer was an environmental battle of the 20th century: ozone depletion was principally caused by the release of fluorocarbons and chlorocarbons. Yes, fossil-fuel-burning by planes does other nasty things to the atmosphere in addition to emitting CO_2. But if someone says 'reduce your CO_2 emissions in order to save the ozone layer', they have got the wrong end of the stick.

'There's a risk that we'll use up all the oxygen'.

False. Yes, climate change is a worry, as is the destruction of natural feedback cycles; but not because we might might run out of oxygen. Oxygen is also the most common element of the earth's crust, by mass. Even if absolutely all the carbon in fossil fuels, soils, and vegetation (5300 GtC) were burned, the amount of oxygen used up (about 14 000 Gt) would be less than 2% of the total oxygen in the atmosphere.

'Burying CO_2 in the ground is a bad idea because it buries oxygen as well as carbon'

Notes

Page 19 of Mott MacDonald paper says the relative warming effect, over 100 years, of methane relative to CO_2 is such that 1 tonne of methane is equivalent to 21 tonnes CO_2. Source IPCC 1995. Nitrous Oxide is next, at 310 to 1. (Check this with IPCC.)

3

Sequestration

Sequestration is the short name for carbon capture and storage.

I'll discuss only two carbon sequestration techniques: geological storage of CO_2, which appears to be a viable and safe method, albeit expensive; then trees, since there are companies out there claiming to neutralize CO_2 pollution by tree planting.

Beware the true motivation for some sequestration projects

Page 6, Energy World (magazine) January 2007. As well as providing low-carbon electricity, the project (new power stations on the East Coast of the UK) 'also opens the door to securing *otherwise unrecoverable oil* from mature fields in the North Sea. [Emphasis added.]

Need to know a source for the estimate of how much storage is available. One very useful figure is the breakdown of CO_2 emissions by 'whether capturable'. In year 2000 Central power stations emit 2.6, direct fuel consumption (Eg buildings, light industry) = 2.2, and transport = 1.4 – total 6.2. (I am surprised that so much of it is in central power places – sounds more than the electricity fraction. Anyway, that means 2.6/6.2 is capturable, but don't forget the leakage rate, perhaps 10% of the CO_2 gets away?

Some important facts about Sequestration

Sucking CO_2 out of thin air has an energy cost, because it is a purification process, putting order into chaos. Sequestering CO_2 into a hole in the ground has an additional energy cost because the gas has to be compressed when we put it down the hole.

Chapter 10 (p. 75) discusses the unavoidable energy cost of carbon sequestration. The energy cost per unit of CO_2 is greater the more dilute the CO_2 is. Sequestration of 1 kg of CO_2 *from thin air* is unlikely ever to be possible for an energy cost of less than **0.7 kWh**. Keith et al. [2005] describe a way of capturing CO_2 from thin air for **3.3 kWh** per kg. By way of comparison, the *release* of 1 kg of CO_2 from burning coal in a power station or from burning gasoline in a car typically *provides* about **1 kWh** of useful energy.

So sequestration from thin air is so energy-expensive, we can hardly contemplate it. If society ever starts sequestering from thin air, it would be wise to stop burning fossil fuels.

On the other hand, sequestration at a place where CO_2 is more concentrated – for example, the chimney of a power station – *is* technically feasible, just. The CO_2 in a chimney is about 500 times as concentrated as CO_2 in thin air, so it costs less energy to concentrate it.

Here's how sequestering could work in a standard coal power station.

Method 1: post-combustion. CO_2 in the chimney at concentration 15% is stripped using amines which are then heated to release the CO_2. (The other gases in the chimney are nitrogen and water.)

Method 2: pre-combustion. Process the fuel into CO_2 and something that's still high in energy (*e.g.*, hydrogen); then burn the high-energy stuff separately. The pre-processing may involve gasification with air or pure oxygen, then reforming. The outputs of the reformer are CO_2 and hydrogen, which must be separated. This separation costs energy.

Method 3: oxyfuel. To avoid the need to separate CO_2 from nitrogen in the chimney, strip the *nitrogen* out of air before the power station, creating pure oxygen. Burn the fuel in pure oxygen; then what comes out of the chimney is pure CO_2. The separation of oxygen from nitrogen costs energy.

In all cases, the CO_2 once captured must be compressed, and water vapour must be removed from it.

Here are the key questions about carbon capture and storage. What is its energy cost? And what is the storage capacity.

Separation methods: sorbents or solvents; membrane; or distillation.

Where to put the CO_2. Geology (IPCC reckon that at least 1000 $GtCO_2$ storable in saline); injection as liquid into deep ocean (depth greater than 1000 m; if greater than 3000 m, CO_2 sinks); react CO_2 with a metal oxide to make carbonates (eg, calcium or magnesium carbonate). (But this is a bad idea because of the big cost of transporting solids around.)

Capacity of the ground

The white paper 2003 says the European capacity for storing CO_2 in geology is around 700 $GtCO_2$, mostly under the North Sea. – About 95% in deep saline aquifers and 5% in depleted oil and gas fields. In

UK areas, there is capacity to absorb *all* UK CO_2 emissions for up to 15 years in oil and gas wells. More (100s) if saline aquifers used.

A 1 GW coal power station produces 6 Mt CO_2 per year. So 100 GW of coal power over 60 years would produce 36 GtC.

So it seems that there is capacity underground.

sequestration

Estimated that between 270 GtC and 2700 GtC could be stored in deep saline formations.

ref www.ipcc.ch (from Jon Gibbins talks)

Sleipner 1 MtCO_2 per year.

Sucking from thin air by enhancing natural carbon-sucking

Idea: CO_2 removal by stimulating calcifying algae in the oceans (the white cliffs of Dover are made of algal calcite).

(More here)

rebuttal:

“Dis-Crediting Ocean Fertilisation”

Sallie W. Chisholm, Paul G. Falkowski, John J. Cullen Science Vol 294 No 5541 12Oct 2001 pp309-310

Notes

Using coal to make synfuels for vehicles would be a step backward in CO_2 terms. Roughly double the CO_2 emissions compared to gasoline.

Sequestration facts

If CO_2 is sequestered in an oil reservoir in such a way that oil companies squeeze out extra fossil fuels which they would not otherwise have extracted, is this a happy side effect, or is it actually a bad thing?

To get a tentative answer this question, it helps to know the **carbon density** of the two liquids involved. The density of liquid CO_2 at high pressure is 1.03 (compared to water, whose density is 1 g/cm^3); I'm not sure whether this density is the appropriate density for the conditions down an oil well, but the density of solid CO_2 is 1.56. The densities of crude oil, diesel, and gasoline are all in the range 0.8–1.0. If we assume the crude oil is mainly hydrocarbon, $(CH_2)_n$, then every 14 g contains one mole of carbon atoms. [C=12; H=1.] So each 16 cm^3 of crude oil contains a mole. Carbon dioxide, on the other hand, has a molecular weight of 44 [C=12; O=16], so every 44 g (or 43 cm^3) contains a mole of carbon.

So CO_2 takes nearly three times more space per carbon atom than crude oil.

crude oil	1/16 mol/cm^3
liquid CO_2	1/43 mol/cm^3

Table 3.2. Carbon density of liquids. CO_2 requires nearly three times more space per carbon atom than crude oil.

If carbon sequestration uses one cm^3 of CO_2 to perfectly displace one cm^3 of crude, which is then burned by a car or plane, the net effect is that *carbon is moved* out *of the ground.* For every tonne of carbon that's extracted and burned, only 16/43 tonnes of carbon are getting put down the hole.

Here's the balance sheet:

Before 'sequestration'	After 'sequestration'
1 ton of carbon in the ground	0.37 tons of carbon in the ground 0.63 tons of carbon in the atmosphere

Or, including the natural-gas power station from which the carbon is being gathered, and assuming that 10% of the carbon burned by the power station gets away at the sequestration plant:

Before 'sequestration'	After 'sequestration'
Gas power station side	
0.41 tonnes of carbon in natural gas, which was recently in the ground	0.04 tonnes of carbon in the atmosphere (assuming sequestration captures 90%)
Sequestration side	
1 tonne of carbon in the ground in virgin fossil fuels	0.37 tonnes of carbon in the ground in sequestered CO_2 1 tonne of carbon in the atmosphere (from oil burned in cars)
Totals	
1.41 tonnes of carbon in fossil fuels removed from ground	1.04 tonnes of carbon in atmosphere, 0.37 tonnes in the ground

Notes: This "cutting CO2 emissions by 90 per cent" guess agrees with [yzhtjw].

Hoping for Technical fixes – Branson launches $25 million climate bid http://news.bbc.co.uk/1/hi/sci/tech/6345557.stm

looking for a method that will remove at least one billion tonnes of carbon per year from the atmosphere.

To encourage a viable technology which will result in the net removal of anthropogenic, atmospheric greenhouse gases each year for at least ten years without countervailing harmful effects.

Notes

For further reading on the natural absorbtion of CO_2 by oceans see www.aip.org/history/climate/Revelle.htm.

4

Bio-nano-solar sequestration technology (Trees)

> "Trees can, over time, remove large quantities of carbon dioxide from the atmosphere. This makes planting a tree an effective way to fight the greenhouse effect."
>
> *50 Simple Things You Can do to Save the Earth*

Figure 4.1. A tree, yesterday.

Is this true? Is tree-planting able to make a significant contribution to the CO_2 balance?

We already discussed trees when we were discussing the idea of using biofuels for energy. We found that biomass was not a very promising way to generate energy on the scale that a 'developed' world needs.

In the previous chapter, we discussed carbon sequestration, and we saw that the fundamental energy requirements for sequestering CO_2 from thin air are so high that it would make little sense to do it. "But trees do it?" you shout. "Trees extract CO_2 from thin air!"

Yes, trees are solar power stations which perform CO_2 sequestration from thin air. But they can't evade the laws of physics. Let's do the numbers.

Land area required for solar-powered CO_2 sequestration

Trees can help absorb CO_2 in two ways, one sustainable and one unsustainable.

The sustainable way to absorb CO_2 with trees is to produce wood from a forest, and *then put the wood*, or at least the wood's carbon, *in a permanent storage place*. This is how fossil fuels were created, for example.

The unsustainable way to absorb CO_2 is to create new forests in areas that currently have little or no biomass, *then guard those new forests from ever being deforested*. This strategy is unsustainable because it steadily uses up empty land; there's only so much barren land we can turn into forest. When I say the strategy is unsustainable, that doesn't mean I think it's a bad idea. Short-term stop gaps may be a good idea. In fact both these sequestration ideas have quite limited scope, as we'll see when we do the numbers.

Sustainable sequestration with trees

According to Smil [1999], managed forests in North America produce 2.5 m^3 (1250 kg) of dry wood per hectare per year, which is .05 kg of carbon (or 0.18 kg CO_2) per m^2 per year. Recall 1/15 kg of carbon emitted per kWh from fossil fuels. So to balance emissions associated with *one person's* fossil-fuel power of 100 kWh per day, you need 50 000 m^2 of forest, *and* a permanent storage place to put 12 m^3 of dry wood per year.

Both these requirements – the area required to make a difference, and the storage required – are problematic. The UK's area is 4 000 m^2 per person; Europe's area is about 9 000 m^2 per person.

The storage is problematic because we would be trying to do the opposite of what the oil companies are doing. If we bury wood in a hole in the ground, how can we guarantee that BP, Shell, or Chevron won't come along and dig it out? Indeed it seems potty to contemplate burying new wood while the fossil giants are still digging up old wood.

There are two storage ideas that might work better than putting wood into a guarded underground repository: charcoal, and combustion with carbon capture and storage.

Charcoal

It's suggested that we could partially burn the wood, making charcoal, which is largely carbon. Charcoal can be added to soil, and is said to enhance the soil's productivity for agriculture. This charcoal would not be used up. It would just sit in the ground looking grubby. Large-scale charcoal-burying thus seems like a useful technology to pursue. But don't forget that, to make a substantial difference, the whole of Europe would have to be turned into a managed forest for charcoal production – and even that scale of forestry would at best balance only one fifth of our current fossil-fuel burning.

Biomass burning with carbon capture and storage

If geological carbon capture and storage is perfected – using saline aquifers for example – then wood could be burned in power station, and the carbon buried in the form of CO_2. This sounds like a good idea to me, but we must not forget that it's subject to the same limit I just emphasized for charcoal production: to bury an amount of CO_2 that's worth writing home about, we'd need to cover the whole of Europe with managed forests. A more realistic plan will be to burn municipal and agricultural waste in power plants, and capture the CO_2 there.

Figure 4.3. Some wood, yesterday.

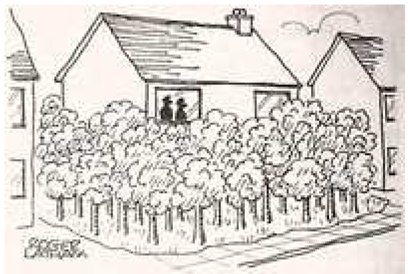
What about forest creation elsewhere on the globe? To absorb 1 Gt CO_2 per year (which is 3% of world greenhouse gas emissions), one needs 5.5 million km^2 of managed forest. For comparison, agriculture currently uses 40% of global land area; and global land area is 148 million km^2. So sequestration of 1 Gt CO_2 per year by managed forest would require an area equal to 3.7% of the world's land, and equal to 9% of the area currently used for agriculture.

Unsustainable sequestration by creation of new forest

If a managed forest is created in formerly barren land, the total amount of stored carbon created after 100 years is about 125 t carbon per hectare of forest. That's 12.5 kg of carbon per m^2 (equivalent to 46 kg of CO_2 per m^2 of new forest).

So, how much new forest do we have to create per year to 'offset' a 100 kWh-per-day fossil-fuel habit? The answer is

$$\frac{10\,\text{tons}\,CO_2/\text{y}}{46\,\text{kg}\,CO_2/\text{m}^2} \simeq 220\,\text{m}^2 \text{ per year.}$$



"We plant a tree every time we fly!"

Figure 4.2. From Private Eye. February 2007.

So one person's lifetime-CO_2-emissions can be neutralized by the creation of 15 000 m^2 of new forest. If you control that much barren land, please go ahead and carefully create a nice managed forest. But please be very suspicious of con-men like `growaforest.com` who claim they will grow trees for you. A company that grows trees on a 10 acre plot (that's 40 000 m^2) has only enough real-estate to service the lifetime emissions of *three* customers!

Best choice of fast-growing tree?

Leucaena is said to produce 25 dry tons per acre per year (62 dry tons per hectare per year). It's a giant perennial tropical to semi-tropical legume which can be grown in places like Florida.

Moringa (Horseradish-tree), a deciduous perennial grown in India and Nicaragua, is more expensive to plant than *Leucaena* but offers bigger yields, if water is plentiful.

Other complications

"Planting forests to combat global warming may be a waste of time, especially if those trees are at high latitudes, new research suggests.

Scientists say the benefits that come from trees reducing atmospheric carbon dioxide can be outweighed by their capacity to trap heat near the ground.

Computer modelling indicates that trees only really work to cool the planet if they are planted in the tropics." [`35yfpd`]

Notes

38 THE STORED CARBON CREATED AFTER 100 YEARS IS ABOUT 125 T CARBON PER HECTARE OF FOREST. Source: IPCC, 2003. Other tree-planting-promoting websites suggest similar numbers, though slightly bigger than those of the IPCC `http://www.carbonfreelife.com/how-work.htm`: "Approximately one tonne of CO_2 will be absorbed in 100 years by 5 healthy trees. "1075 native, deciduous, broadleaf sapling trees planted on an acre of land will secure the natural sequestration of around 215 tonnes of carbon in the trees and immediate biosphere over a period of 100 years of growth." [That's 53 kg of carbon per m^2, which is four times as big as the IPCC's 12.5 kg per m^2.]

5

Ethics

Global pollution and ethics

I'm a scientist, not an ethicist, and in most of this book I focus on numbers and facts, so as to clarify what our options are for making a difference.

Action to prevent catastrophic climate change is an ethical issue, however, so let me spend just a couple of pages discussing ethics.

Let's discuss a cartoon world in which the total pollution is 30 billion tonnes of CO_2 per year, and the population is 6 billion. The average pollution is therefore 5 tonnes per year per person (figure 5.1a), but the actual pollution per person is not uniform. As shown in figure 5.1b, the cartoon world has two regions: a 'rich' region, which has *one third* of the population and emits *two thirds* of the pollution; and a 'poor' region, which has *two thirds* of the population and emits *one third* of the pollution. Each rich person emits 10 tonnes of pollution per year (twice the world average). Each poor person emits 2.5 tonnes per year (half the world average).

Let's assume, to simplify discussion, that it's agreed that we need to halve total global pollution by 2050 to avoid catastrophe. Several plans

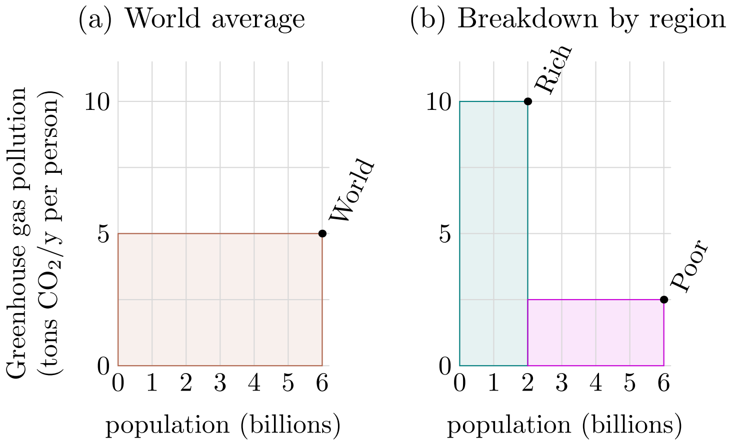


Figure 5.1. The situation on our cartoon world today.

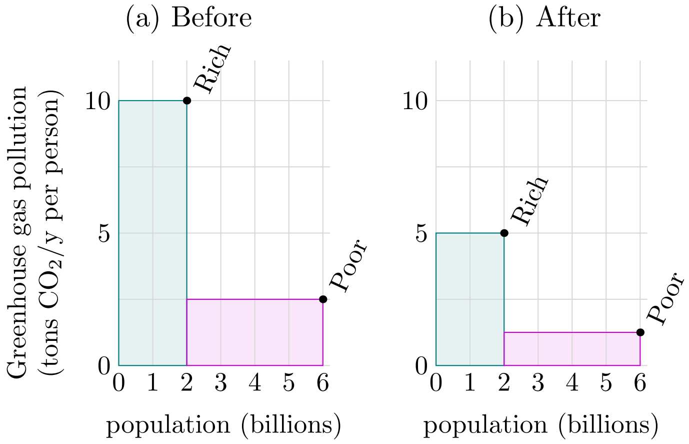


Figure 5.2. Plan A.

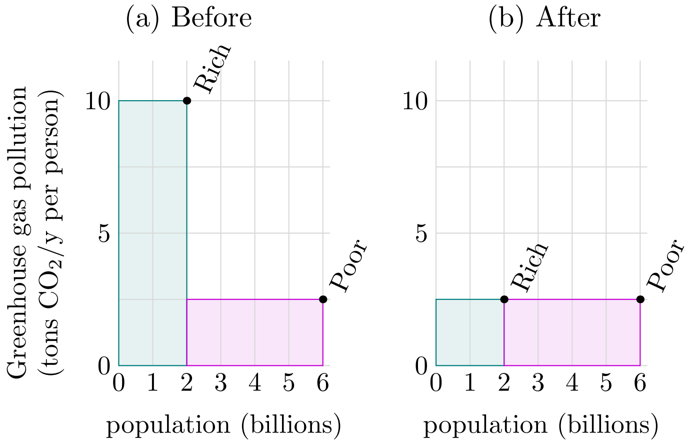


Figure 5.3. Plan B.

can be proposed for achieving this goal. Under plan A (figure 5.2), everyone halves their pollution. Under this plan the rich still emit four times more pollution than the poor. The poor might well object to this plan: "it's you rich guys who pumped carbon into the atmosphere over the last 50 years; why should we help you out of the mess you've got us all into?"

Under plan B (figure 5.3), the target is for everyone to emit equal pollution, per capita. This plan (known as convergence) requires the rich to reduce their pollution by a factor of four, and requires no change in the poor's pollution.

Plan B2 (figure 5.4) introduces a small change from plan B: everyone is *permitted* to emit equal pollution, per capita, but these pollution permits are tradable in a cap-and-trade system. As a consequence, the poor eagerly sell most of their pollution permits to the rich, and we obtain a situation quite similar to plan A. The rich reduce their pollution by 37%, and the poor reduce theirs by 75% (and receive cash from the rich).

Plan C (figure 5.5) introduces another way of halving pollution,

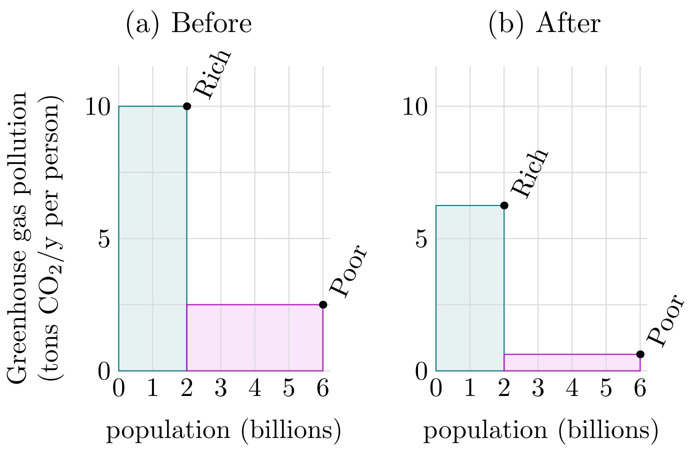


Figure 5.4. Plan B2.

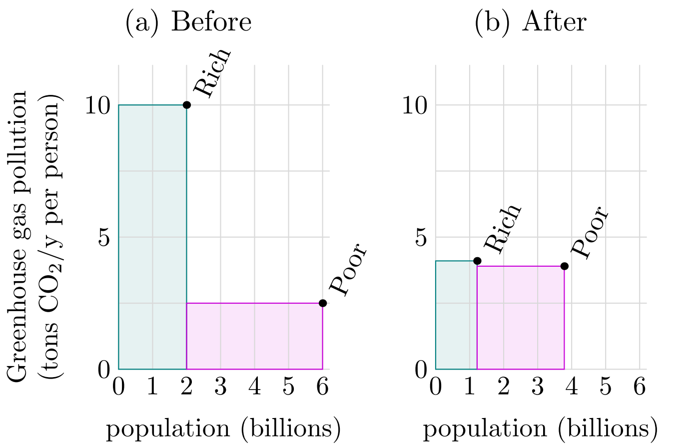


Figure 5.5. Plan C.

namely population reduction. In this plan, the world population is reduced by about one third. This allows the world to get by with a higher per-capita pollution target.

Which of these plans is ethical? I don't know, but I find these cartoons a helpful aid to discussion. There seems to be some consensus on the idea of 'convergence' (plan B) and also a love, in some parts of the world, of 'cap and trade' (plan B2). But I am struck by one problem with the idea of equal per-capita pollution rights. If pollution rights are given out per capita, countries will feel an incentive to *increase* population. Which is how we got into this mess in the first place! Imagine a world with two identical continents. If the people on one continent choose to have population growth, and the other continent's population is kept constant, what is the ethical assignment of pollution rights? Is equal per-capita fair? Perhaps pollution rights should be granted per unit land area?

Stern and discounting

People criticised the Stern review for using a small discounting rate in his economic calculations. Stern has robustly defended his choice in ethical terms. I'm no economist, so my opinion on these matters carries no weight at all, but I thought it might be helpful to other non-economists if I at least tried to express in plain language what the discounting kerfuffle is about.

I'll ask you a few questions.

Round 1

Imagine that I give you the choice of receiving a favourite luxury now, or in one year's time. Which would you prefer?

Or imagine that I give you the choice between having a rock dropped on your toe now, or on a day in one year's time. Which would you prefer?

Round 2

Imagine that you are in control of a device for giving out free luxuries, and one of your choices determines the allocation of one hundred luxuries between two people called Joe and Fred. You know neither Joe nor Fred, Joe and Fred don't know each other and don't know you, and you don't know any way to distinguish them. How do you share out the luxuries – fifty to Joe and fifty to Fred? Or do you give more to one and fewer to the other? Think ethically.

Imagine you are in control of an inexorable rock-dropping device, which will certainly drop a rock either on the toe of Joe or on the toe of Fred. You are responsible for setting a dial that controls the probability that the rock drops on Joe rather than Fred. How do you set the dial? Do you not care?

Round 3

Imagine now that the situation is just like round 2, except that if Joe receives luxuries from your device, he is guaranteed to get them *now*, whereas if Fred receives luxuries, he is guaranteed to receive them *in exactly one year*. Does this affect the way in which you share out the one hundred luxuries between them?

Similarly, if you have control of the probability that the rock gets dropped on Joe rather than Fred, and if in addition the hitting of Joe, if he's chosen by the device, would happen today, whereas Fred, if chosen, would be hit in a year's time, would ethical considerations lead you to set the dial differently from the way you set the dial in round 2?

Round 4

There's two groups of people, group J (one million people), and group F (also one million people). You have a choice between (A) *both* giving two million luxuries to group J now, *and* dropping rocks on the toes of everyone in group F in one hundred years' time; or (B) giving one million luxuries to group J now and one million to group F in one hundred years' time, and dropping rocks on the toes of half of the people in groups J and F at the two same times. What's the ethical choice?

[That was too complicated. Display the choice somehow.]

Reflection

If you're like me, your answer to the first group of questions might be 'I'd prefer to have the luxuries now, and the pain later'. If so, this is an example of standard discounting. Indeed we tend to take a bit of extra pleasure *now*, even if that might imply some pain for us in the future. We value possessions, luxuries, and other good things less if they to be had in the future rather than now. To get a particularly convincing example of this, imagine that you have a choice between receiving one million pounds today, or receiving one million pounds on the day the doctor signs your death certificate. One million pounds has much less value to you if you can't spend it.

However, if you're like me, your answers to the other questions follow a different pattern. Ethically, it seems right to treat Joe and Fred equally, even if they live at different times from each other. If we were convinced that in the future, everyone on the planet is going to be much more wealthy than people are now, then maybe we would bias things a little in favour of the contemporary Joe rather than future Fred. But if the rules of our imaginary game instruct us that actually the conditions of Joe and Fred will be much the same (before we drop luxuries or rocks on them), then it's hard to justify treating one of them better, just because he happens to live at a slightly earlier epoch. What do you think?

The fourth example, I imagine you've noticed, is intended to mirror the major ethical question of climate change. Does the ethical choice prioritize the happiness of one million people in the future equally with the happiness of one million people now?

In terms of these cartoons, we can now explain Stern's position on discounting. Stern says, yes, if you are an individual or a corporation balancing your *own* happiness now against your *own* happiness in the future, you may well use discounting, valuing a bit of *your* happiness now more highly than an equal amount of *your* happiness in the future. However, Stern says, when balancing the welfare or one million people now against the welfare of another group of one million people in one hundred years' time, those welfares should be valued almost equally.

We should not expect market interest rates to coincide with the ethical value of future wealth compared with wealth today. Just because *I* and many forty-year old investors have very little interest in owning any possessions in 2067 (because we're not expecting to be around then), that doesn't mean that society should view all assets in 2067 as having no value.

Personal discounting rates and corporate discounting rates are different from ethical discounting rates for valuing human happiness.

6

'Neutralization' and pollution trading

> All government activity will be carbon neutral by 2015.
>
> *Prime Minister's spokesman*, 9 January 2007

> Companies and individuals rushing to go green have been spending millions on "carbon credit" projects that yield few if any environmental benefits.
>
> *Financial Times*, 25 April 2007

Does 'neutralizing' CO_2 add up? Is 'offsetting' sustainable, or is it just greenwash? What about green electricity?

Tall tales from the World Traveller section

It was on a flight with British Airways that I had my first encounter with carbon-neutralization. What I read in BA's in-flight magazine made my jaw hit my tray-table.

> **What impact does your flight have on climate change?**
>
> Every flight you take has an impact on climate change that arises from the carbon dioxide (CO_2) from burning kerosene and other effects in the upper atmosphere. British Airways supports a long-term approach to tackling this impact...
>
> YOU CAN TAKE RESPONSIBILITY FOR THE IMPACT OF YOUR FLIGHT
>
> British Airways has joined forces with an organisation called Climate Care to enable you to offset the CO_2 emissions created during your flight.
>
> You can click on the calculator button to calculate your share of the emissions created during your journey and the cost of neutralising the impact of those emissions. If you decide to

> pay this cost, the money raised will be used by Climate Care to fund sustainable energy projects around the world on your behalf.

When you follow BA's instructions, you discover that on a typical round-trip flight on a 747, your emissions are 2 tons of CO_2; and the cost to offset this CO_2 is just £15.00! – a mere 2% of the price of your ticket.

Who imagined that saving the planet would be so easy? Thanks to good old Climate Care, you can carry on living like a king. A typical European's entire annual emissions of 10 tons of CO_2 can be entirely neutralized for just £75. How happy one must feel when one receives absolution from Climate Care!

I think Climate Care's heart is in the right place, and I admire what they do in the developing world, but I have grave concerns about the effect of the cheap get-of-jail tokens that they are dispensing. I worry that their people here will get the message that neutralizing CO_2 is pretty easy, and that there's no need for radical change.

How do Climate Care arrive at this figure of £7.50 per ton of CO_2?

Here is my cartoon version of Climate Care's activity, told in the form of a story.

The story of Joan and Thabo

Joan has just taken a round-trip to Johannesburg and wishes to 'neutralize' her CO_2 emissions. She contacts Climate Care. They say, "no problem, we are in contact with a trustworthy South African named Thabo. Thabo owns half a ton of coal, and he intends to keep his family warm over the next year by burning that coal. However, if you pay us £15, we'll pay him £8*, which Thabo can use to buy thermal underwear for himself and his family; the underwear will last them all year, and Thabo promises he won't set fire to the coal." Joan's two tons of CO_2 emissions are thus neutralized by this 'offsetting'.

*Only a little over half of Joan's donations goes to the developing world; the rest pays for the Climate Care organization.

The actual balance sheet: Joan emitted two tons of CO_2 on her trip. Thabo *would have* emitted four tons that year (two tons by burning their coal, and two tons by other activities (car-driving, electricity consumption, etc.); instead, thanks to Climate Care's intervention, and Joan's generous donation, Thabo emitted just two tonnes.

The net impact is that Joan and Thabo together have contributed four tons of CO_2. Is it accurate to say that Joan's pollution has been neutralized? Is she a zero-carbon flyer? I think it is more accurate to say that Joan is in a partnership with Thabo, such that their *joint* pollution was four tons over the year. Notice that no CO_2 has been sequestered, sucked up, eliminated, or destroyed. The partnership has emitted an unsustainably large amount of pollution, albeit less pollution. The partnership is not carbon neutral. It is not zero-carbon.

Now, what about next year? Joan again goes on a trip that burns one ton of fossil fuel. Anxious to make 'no contribution to climate change', she again contacts Climate Care. And Climate Care say "no problem, we know a South African named Thabo; he is still sitting on a half-tonne of coal. His thermal underwear has worn out and his wife just gave birth to twins, so Thabo intends to burn the coal this year, unless we can ship some more long-johns to him. It'll cost you £15." Joan pays up. Thabo and family receive the long johns. The half-tonne of coal goes unburned. The total pollution by the Joan–Thabo consortium was again 4 tons of CO_2.

The following year, guess what happens? Joan makes another trip, and Thabo still owns that convenient pile of coal. Joan's two tons of pollution are again miraculously 'neutralized' by Thabo's helpful agreement not to burn the half-tonne of coal.

All these avoided emissions are carefully monitored by Climate Care's distinguished partners, and Climate Care's sums are confirmed to be correct by the Oxford Environmental Change Institute. "Yes," they confirm, "on every occasion, the intervention of Joan and Climate Care avoided two tonnes of South African emissions that would otherwise have been inevitable."

For how many years can Joan fly 'Carbon-free'? Well, it seems that as long as Thabo never burns that little pile of coal, he can help Joan 'neutralize' her emissions every year, once a year, in perpetuity!

It's a Climate Care miracle! A bit like the feeding of the five thousand with just five loaves.

Does this miraculous story make sense? Or is it poppycock? Can Climate Care's miracle be scaled up in order to neutralize the emissions of everyone in Europe?

I think a good analogy is to imagine that Joan and Thabo are passengers in a large sinking boat. The flooding of the boat is analogous to rising CO_2 levels. Joan's actions drill an extra hole in the boat, increasing the rate of flooding. Feeling guilty, she spends some money to help Thabo reduce the size of *his* hole. Great – the boat is still sinking! The actions of Joan and Thabo do not deserve to be called "flooding-neutralization".

Here's another version of the Joan–and–Thabo story. Joan pays the cash, and £8 is sent to Thabo for super-duper house insulation so that he doesn't need his half-tonne of coal. Straight away Thabo realises he doesn't need the coal any more, and he sells it to his cousin Themba, who is thinking of heating his chilly house with it. The same day, Joan's cousin Janice makes an international trip with her favourite airline, and having heard how Joan's guilt about flying had been lifted by Climate Care, Janice pays them £15. Climate Care say "no problem, we happen to know a trustworthy South African named Themba and we have confirmed that he is about to set fire to half a tonne of coal. Only with your donation can this be prevented." The next week, Themba sells his now unwanted coal to Tichaona...

I think this cartoon is relevant to offsetting schemes. One action by an offsetting company may prevent some fossil fuel from being burned in some location. But that's not the final effect of the offsetting action. What other knock-on effects occur, thanks to the fossil-fuel market? For example, if Climate Care put twenty low-energy lightbulbs in all the houses on Thabo's street, thus "saving a tonne of CO_2 over the life of the bulbs, because those houses' electricity comes from an oil-fired power station" is the tonne of CO_2 emissions truly avoided? I expect that the energy market will respond ever-so-slightly to the slight drop in electricity demand produced by the bulbs. The electricity company might respond to a drop in demand by reducing electricity prices a little, thus ensuring that they sell exactly the same amount of electricity, and burn the same amount of oil. Or if the electricity company keeps its prices constant, it will use a bit less oil at its power station; does that mean less oil is used worldwide? I doubt it. If less oil is bought by one buyer, the price drops a little, and some other buyers step up and buy the cheaper oil. As I write, oil prices are 'alarmingly high'. Surely in such a market most oil producers are producing oil as fast as they can. So offsetting schemes don't even delay carbon emissions. They just change who is doing the emitting, and give delusional feelings of 'carbon neutrality' to Joan and Janice.

I'm not denying that Joan and Climate Care have done a good thing. I applaud all efforts to undo the exploitation of Africa. But the Joan–Thabo consortium *has* actually emitted 4 tons of CO_2 pollution per year.

I think that what Climate Care *ought* to do, if they want to salve Joan's conscience, is help her form partnerships whose net emissions are *zero*. This would be far more expensive for Joan! For a Joan–Thabo partnership to emit zero CO_2, Joan would have to first arrange for Thabo to obtain entirely fossil-fuel free electricity, for example by erecting a community wind turbine, by solar panels, or by cultivation of biomass fuels for use in the local power station. This could reduce Thabo's emissions to near zero. But then we still have Joan's luxury jet emissions to deal with. To achieve *zero* emissions, Joan needs to pay for two tons of CO_2 to be sequestered somehow. For example Joan must get Thabo to grow a new sustainable forest sufficiently large that he can *put three* tons *of wood permanently beyond use every year.* All that wood would have to be carefully guarded to make sure that no-one ever burns it. Or she must pay Thabo to extract CO_2 from the air in some other way; whatever is done, the extraction of CO_2 from thin air has a significant energy cost. Simple thermodynamics leads to an estimate of 100 or 200 pounds as the realistic cost of this sequestration, as we'll see later in chapter 6. One Joan is going to have to partner with many Thabos! If everyone who flies did this, I suspect there wouldn't be enough Thabos to go round.

In sum, it's financially easy to *reduce* CO_2 pollution a little in a world with huge financial inequities. You just find someone poor, and get *them* to do all the reducing. That's the 'economically optimal' solution. But Climate Care aspires to help people transform their lives so that climate change is not reduced but halted. And thus CO_2 pollution must be not *reduced*, but *eliminated*. Eliminating CO_2 pollution requires activities of a completely different kind, whose cost will be much higher.

So, what is the true cost per ton of CO_2? I'll discuss this in a couple of pages

Carbon trading or carbon tax?

One of the widely discussed methods for reducing carbon pollution is 'cap and trade'. In the cap and trade system, politicians decide, for each year, a cap on carbon pollution; and they decide how to allocate 'emissions permits' – or, as I'll call them, 'pollution permits' – to corporations, or even to individuals. The European emissions trading scheme (ETS) is a cap and trade system, erected in January 2005. Bizarrely, the European system gave out pollution permits to corporations *for free*, and *in proportion to their historical emissions* – so corporations that have historically been the worst polluters were given the most pollution permits! This sort of cap-and-trade system is not popular with many American politicians, and I think they are right.

After all, if we decide that we want to reduce the murder rate, do we give out a restricted number of murder permits to be traded among those who want to commit murders? To eliminate slavery, did we set up an international slave trade? Why should pollution be different from murder or slavery?

The idea of giving everyone a personal carbon credit card seems rather odd if you remember that carbon is not the only form of pollution. Sulphur emissions cause acid rain. Particulate emissions cause smog and asthma. And legislation has successfully reduced both sulphur and particulate pollution without the need for every human on the planet to be issued with either sulphur credit cards or personal particulate pollution passes.

An alternative and simpler way to get the marketplace to reduce carbon pollution is to introduce a carbon pollution tax or levy. (Sweden and Norway have successfully used such carbon taxes.) The carbon tax would be paid at the point of extraction of carbon from the ground or at the point of import of carbon into the economic community where the carbon tax applies. The only organizations that would have to deal directly with the carbon pollution tax would be the few large corporations involved in the extraction and transport of carbon. These corporations would then pass on the carbon costs to consumers of their goods and services through normal economic channels. There would be no need to give out any 'pollution permits'. The price of carbon-intensive goods and services would be simply and precisely passed on in the price paid by the consumer.

Governments could use some of the pollution taxes collected to pay for pollution clean-up – for example, paying the costs of proven carbon sequestration. The carbon tax would have the biggest effect if it were introduced as a replacement for existing 'brown' taxes, that is, taxes that don't encourage environment-friendly behaviour; for example if carbon tax replaced value-added tax, the tax per tonne of CO_2 could be set to a larger value. The tax burden on a typical person would be little changed, but the price signals favouring carbon reductions would be stronger.

The carbon tax could be controlled by an independent body responsible for ensuring that total emissions match or exceed a desired trajectory.

Other carbon pricing systems have similar effects to a carbon tax. In the cap-and-share system, the number of tons of pollution permits is fixed, and the pollution permits are auctioned to the companies that wish to import or mine carbon-containing fuels. (So the permits are required at the upstream end of the carbon distribution chain.) The proceeds of the auction are distributed equally to all adults in the population. This system is very similar to having a carbon tax and a welfare state, which distributes to everyone a minimum wage proportional to the carbon tax. If the auction starts at a minimum price that is announced years in advance then cap-and-share provides similar confidence in low-carbon investments to a carbon tax.

What's the value of a tonne of carbon dioxide?

Let's assume that many countries agree to have a cap-and-trade scheme or a carbon tax. What will the price of CO_2 pollution need to be, if the cost of carbon is to make a significant difference to people's behaviour? Remember, the goal is to reduce Europe's pollution from roughly 10 tCO_2 to 1 tCO_2 per year. Conventional wisdom asserts that the European Commission 'over-allocated emission rights for the first three years of the emission trading scheme'. So the price of a permit to emit one tonne of CO_2 pollution is presumably destined to rise above its range in 2005 (€7–29) and 2006 (€10–31). The carbon offsetting companies tell you that one ton of CO_2 guilt can be magicked away for about €10 (£7.50 or so). I normally avoid questions of economics, but I feel compelled to explain why I think this price is outrageously low.

The aim of putting a price on carbon pollution is to get people to modify their behaviour.

If we can identify the *value* that people place on an activity that emits one tonne of CO_2 pollution, we can anticipate market prices at which society's lifestyle would be significantly transformed.

If a single ticket to Johannesburg emits one tonne and costs £400, for example, and if all governments agreed that CO_2 emissions cost £7.50

per ton, *would people who fly fly less*? You don't need to know much about the 'elasticity' of this market to know that the answer to this question is *No*. People will fly less only if the CO_2 cost grabs their attention sufficiently against the backdrop of the £400 plane ticket.

We can also estimate bounds above which the price of pollution permits should not rise by estimating the costs of methods of largescale carbon dioxide *capture*.

The actual price of CO_2 will always depend critically on the cap chosen. It's crucial that this cap be chosen wisely. Setting the cap to a value that has a significant effect on pollution will doubtless cause disgruntlement, so we must ensure that cap-setting is not left in the hands of politicians who might care about the short-term reactions of the disgruntled more than the long-term health of the planet.

The value of CO_2 pollution, in energy terms

What is the exchange rate between energy and CO_2? The exchange rate depends on the fossil fuel, and what sort of energy we're talking about. Perhaps the most useful exchange rate to know is the amount of CO_2 pollution emitted when one kWh of *electricity* is created by burning fossil fuels. It's easy to remember:

$$1\,\text{kg}\,\text{CO}_2 \leftrightarrow 1\,\text{kWh}\,(\text{electricity}).$$

This figure (1 kg per kWh) is the exchange rate for a coal-burning power station. The best gas-burning power stations emit $1/2$ kg CO_2 per kWh of electricity.

So one tonne of CO_2 pollution is emitted when people buy 1000 kWh of electricity from coal-burning stations (which costs the householder £100 at a price of 10p per unit), or when they buy 2000 kWh from natural-gas-burning stations (which costs £200). These figures tell us neither what the price of CO_2 pollution will be, nor what it should be; but they do define an interesting benchmark: if the price of CO_2 pollution were **£200 per tonne**, and if fossil-fuel-burning power stations didn't get any crazy free permits, then the price of electricity from gas-burning stations (that did no carbon sequestration) would double, the price from coal-burning stations would triple, and the economic benefits of renewable energy would be greatly increased. If gas were plentiful, then this would be the end of coal. But gas may become scarce in a few decades, so I'll include coal in the comparisons that follow.

Let's look at this from the point of view of an investor considering funding a tidal or offshore-wind power-generation project. Imagine that the cost of the renewable power is expected to be about 3p per unit more than the cost of electricity from a conventional gas-burning station. That 3p difference would be eliminated if CO_2 credits cost £60 per tonne. For big investors to back such renewable energy projects, they must therefore be convinced that CO_2 will be worth more than **£60 per tonne** for several decades to come.

As I mentioned above, the price of a one-tonne CO_2 pollution permit has ranged from €10 to €31 (£7–21; $13–39) in 2006. In phase I (2005–07) of the EU emissions trading scheme, the price of carbon dioxide was capped at €40 per tonne (the excess pollution penalty that must be paid if a polluter pollutes without an allowance). In phase II (2008–12), this cap rises to €100, but it seems the UK government assumes the price will not rise above about €36.

Impact on car travel

In the UK, petrol costs £1 per litre (that's $7 per US gallon). One litre creates roughly 2 kg of CO_2 pollution. So for the price of CO_2 pollution to significantly impact car-driving in the UK, CO_2 pollution would need to cost about £500 per tonne ($900). Here, I'm assuming that a doubling of the price paid for fuel would have 'significant impact'; as evidence, recall the history of the Fuel Price Escalator, a steadily-increasing fuel tax introduced under the Conservative government in 1993, and the fuel protests of 2000. From 1995 to 2000, the price of petrol had risen from 54p to 76p per litre. This gradual rise amounted to less than a doubling in price, but it certainly led to some behavioural change – for example, the behaviour of the fuel protestors. (The end to the escalator was announced on November 9, 2000.)

In the USA, petrol costs $3 per US gallon ($0.79 per litre, or 43p per litre). So for the price of CO_2 pollution to significantly impact car-driving in the USA, CO_2 pollution would need to cost about $400 per tonne.

CCS: On p193 of govt energy review, they assume Carbon Sequestration cost is 8 pounds per tonne of CO_2.

Domestic heating

The pollution associated with burning gas to obtain one kWh of heat is about $1/4\,\text{kg}\,CO_2$. In 2000, gas cost 2p per kWh to a domestic customer. At that price, you're paying $2\text{p} \times 4000 = £80$ every time you emit a tonne of CO_2 pollution. So, CO_2 pollution would have to cost of order £80 per tonne for consumers to really notice the effect on their heating bills.

Barrel of oil

As I write, a barrel of oil costs about $90. So what does it already cost to emit a ton of CO_2? One barrel gives rise to about $0.4\,tCO_2$, so at $90 per barrel, barrel-buyers pay $225 per tonne of CO_2.

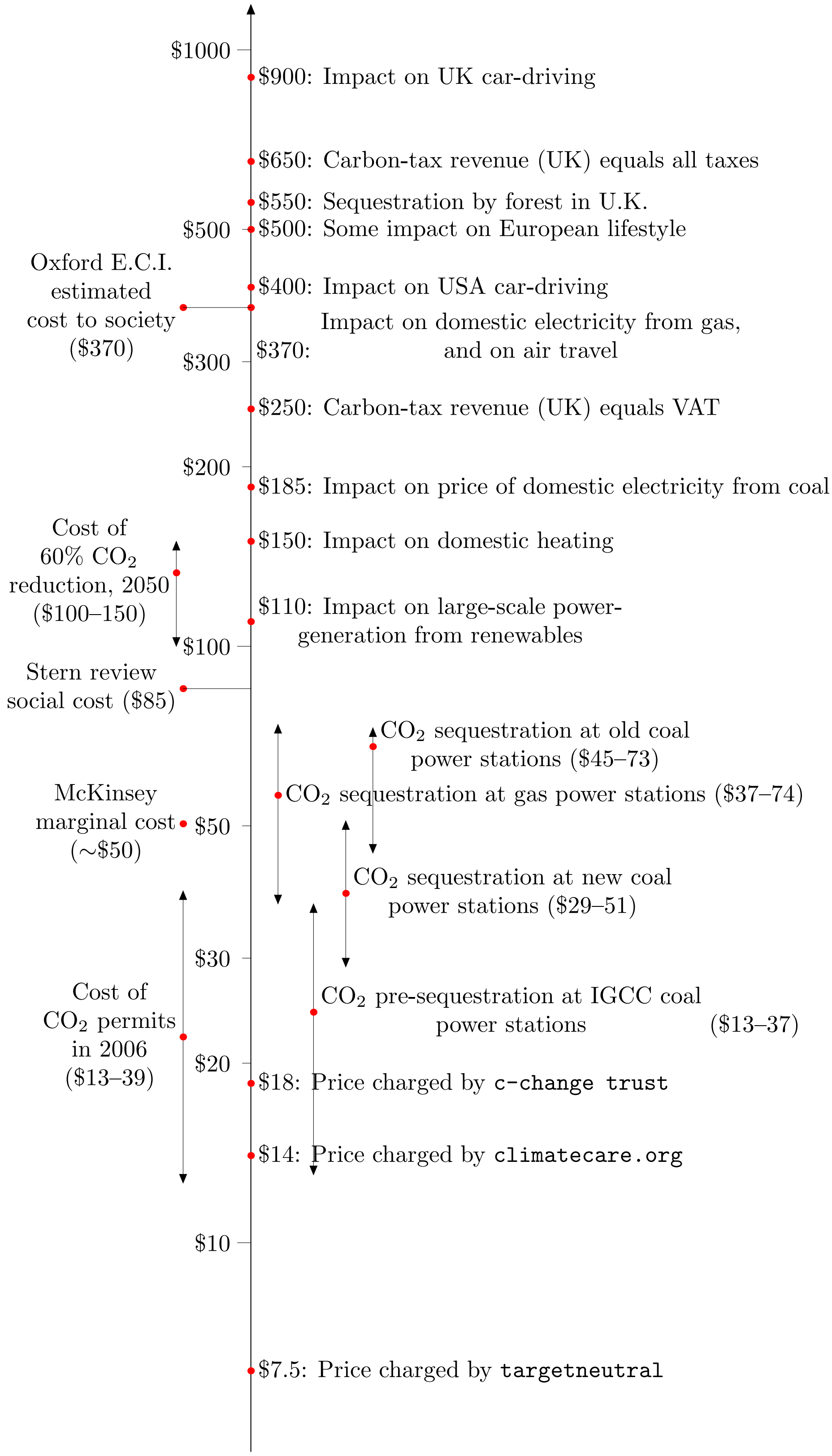


Figure 6.1. What would CO_2 prices need to be in order to drive society to make significant changes in CO_2 pollution?
Carbon dioxide costs (per tonne) at which particular actions will become economical, or particular behaviours will be economically impacted.
As the cost rises through \$20–70 per tonne, CO_2 would become sufficiently costly that it would be economical to add carbon sequestration to new and old power stations.
A price of \$110 per tonne would transform large-scale renewable electricity-generation projects that currently cost 3p per kWh more than gas from pipedreams into financially viable ventures. For example, the proposed Severn barrage would produce tidal power with a cost of £60 per MWh, which is £33 above a typical selling price of £27 per MWh; if each tidal MWh avoided one ton of CO_2 pollution at a value of £60 per ton, the Severn barrage would more than pay for itself.
At \$150 per tonne, domestic users of gas would notice the cost of carbon in their heating bills.
At \$370, carbon pollution would cost enough to reduce people's inclination to fly.
At \$500 per tonne, average Europeans who didn't change their lifestyle might spend 12% of income on the carbon costs of driving, flying, and heating their homes with gas.
And at \$900 per tonne, the carbon cost of driving would be noticeable.

Home electricity production

Putting up solar panels is a form of do-it-yourself carbon offsetting, and it gives a good benchmark price for CO_2 pollution.

If local government planning permission can be obtained, my domestic photovoltaic panels will cost £7000 and will hopefully generate about 1300 kWh per year for 25 years. If we assume these panels will prevent fossil fuel burning to the tune of 0.43 kg CO_2 per kWh (the standard guideline figure today), then the panels will reduce pollution by 14 tons over their lifetime (neglecting the carbon cost of making the panels in the first place!). The price per ton of CO_2 pollution avoided is thus

$$\frac{7000}{0.43 \times 25 \times 1300/1000} = \pounds 500 \text{ per ton.}$$

Flight

Another benchmark comes from the trusty 747. One passenger's share of CO_2 pollution on an intercontinental round trip on a 747 is about two tons. [In fact, the climate-change effect associated with pollution by a plane is said to be roughly twice as bad as CO_2 pollution at ground level.] The cost of such a trip at present is about £400–700 in peak Summer 2006, and £330–650 at other times of year. How much would the cost of the CO_2 pollution permits for such a trip need to be in order to affect peoples' behaviour? A price of **£200 per tonne** is a good benchmark ($370): at this price, the CO_2 cost would double the price of typical cheap tickets; and standard tickets would go up by 40% – enough to affect some people's behaviour. If the cost of CO_2 pollution is really going to reduce air travel significantly, I guess the price would have to be about **£400 per tonne** ($700).

Thus as the price of CO_2 pollution increases, we should expect society to change the way it generates electricity before it stops zooming around in planes.

'Carbon poverty'

In the UK, someone is said to suffer from 'fuel poverty' if she spends 10% or more of her income on fuel (that is, on gas and electricity). We could similarly define 'carbon poverty', if carbon pollution had a price, by saying someone suffers from carbon poverty if 10% or more of her income pays for carbon pollution. Using this notion, we can estimate how costly carbon would have to be in order for a typical British person who *doesn't* change her lifestyle to enter carbon poverty.

(This is repeated later on.)

The carbon cost implicit in subsidies

We can view the subsidies given to renewable-energy providers as implying a carbon value. If a renewable obligation certificate (ROC) has a value of 5p per kWh of electricity, and if each renewable kWh avoids 500 g of CO_2 pollution, then one tonne of avoided CO_2 pollution is implicitly valued at $2000 \times 5\text{p} = £100$.

However, the intended purpose of ROCs is perhaps not only to pay for reductions in CO_2 pollution today, but also to support research and development.

The true figure is much higher.

The cost to consumers of carbon abatement through the RO has been £110 per tonne of CO_2. `http://www.ofgem.gov.uk/Sustainability/Environmnt/Policy/Documents1/16669-ROrespJan.pdf`

Carbon purchases comparable to developing world's aid, or GDP

Imagine that tradable carbon credits are given by the United Nations to everyone, per-capita: pollution rights of, say, 1.2 tonnes CO_2 per person per year. This constraint would cap CO_2 pollution at the 'safe' level of 2 GtC per year mentioned on p.14. Such a cap would require the average European to make an eight-fold reduction in emissions, or to buy pollution permits from others to make up the difference; the average American would have to make a sixteen-fold reduction, or buy from others. Imagine that the European Union and the US respond by buying 1 billion tonnes of pollution permits from Africa (corresponding to most of that continent's permits).

If CO_2 pollution cost $25 per tonne, the value of African pollution credits would approach the total aid budget for Africa ($26 billion). At this price an average European would have to pay only $210 per year to keep her lifestyle unchanged.

If CO_2 pollution cost $40 per tonne, the mass-purchase of African pollution credits would exceed the USA's imports from Africa ($36 billion). At this price, a European would have to pay only $340 per year to keep her lifestyle unchanged.

If CO_2 pollution cost $500 per tonne, the value of African pollution credits would approach Africa's GDP ($558 billion). At this price, a European would have to pay about $4000 per year to keep her lifestyle unchanged. If her salary were $34 000, the extra CO_2 credits would be costing 12% of her salary. Incidentally, this benchmark '12% of income devoted to paying for carbon credits' is close to the UK's definition of 'fuel poverty': someone is in fuel poverty if she spends more than 10% of her income on fuel (for example, domestic gas and electricity bills). $500 per tonne is therefore a carbon price at which we could expect to Europeans make substantial changes in lifestyle.

These benchmarks are interesting because they help clarify what behaviour changes we can expect to be brought about if carbon pollution were made more costly. The whole idea of carbon-pollution trading is to change people's and companies' behaviour, right? So, for example, if governments hope to reduce travel by road and air through carbon trading, they must ensure that the price of carbon pollution goes above $150. As the price rises, other behaviours will change too: owners of power stations will introduce carbon sequestration; coal power stations will close down; more renewable power systems (tide and deep offshore wind) will become competitive; people will become more interested in reducing their heating bills.

If governments do *not* take actions that lead to carbon costing about $150 per tonne of CO_2 – if it stays below $50 per tonne, for example – then we can't expect *any* major impact on people's lifestyles. Carbon trading would be a charade. For most Europeans, carbon payments would be only about 1% of annual income, so who would care? Power stations may install sequestration technology when the price is $50 per tonne, but ordinary people will feel little incentive to modify their fossil-fuel heating system, to change their car-driving habits, or to reduce their air travel.

Wind

According to the DTI's projections DTI [2007], onshore wind has a cost of £50 per tonne of CO_2 emissions avoided ($90), and offshore wind has a cost of £82 per tonne of CO_2 emissions avoided ($150).

To do: include comparison with tax in the text.

About offsetting

Mr. Miliband said offsetting "isn't the answer to climate change". Thu 18/1/07

Some value judgements

> Market mechanisms are a game of creative accountancy that distracts us from the fact that there is no viable 'business as usual' scenario.
>
> *Kevin Smith*, Carbon Trade Watch

> The EU Emissions Trading Scheme is a cost-effective way of not having to take effective action.
>
> `http://www.carbontradewatch.org/`

I'm trying to play the impassive objective scientist, but I feel the urge to blurt out a value judgement: I think "carbon offsetting" that costs less than $20 per tonne is evil, because it leads to inaction on the part of wealthy people. Someone who emits 10 tonnes of CO_2 pollution per year can "offset" the lot for $200 per year and may thus feel no incentive to reduce their CO_2 pollution; indeed the companies that urge them to "offset" in this way will reassure them that by offsetting they have 'been responsible' and 'done their bit'; they'll feel that they can justify any extravagant consumption or waste by saying 'don't worry, I'll offset it'. The worst offsetting organization of all is BP's `\ind{targetneutral}`, who sell carbon indulgences for such a low price ($7.5 per tonne) that I had to extend figure 6.1 by an inch to fit them on.

Cost of sequestration from the air

Unavoidable laws of physics guarantee that the energy cost of creating one kg of liquid CO_2 from thin air (that is, not at a power station or similar source where CO_2 is more concentrated) is 0.24 units. Assume a factor of 3 for inefficiency, then we have 0.72 units per kg. So 720 units per tonne of CO_2, which costs about £20 at retail price of 3p per unit ($37); or £72 at 10p per unit ($130).

This is a theoretical possibility only: I don't know whether any technologies could sequester CO_2 at this price; and these prices don't include the cost of transporting and storing the CO_2 once it is captured.

Sequestration by forest-creation

One way of reducing CO_2 levels is to buy a piece of land without vegetation, grow a forest on it, and commit never to cut the forest down. REWRITE USING THE IPCC FIGURES. Typical mature forest contains 25 kg/m^2 of 'standing phytomass'. So assuming that corresponds to 5 kg of Carbon per m^2 (half for conversion to dry mass, and 2/5 for Carbon to carbohydrate ratio), each m^2 sequesters about 20 kg of CO_2.

If we assume we can pick a location where creating and maintaining the forest has negligible energy costs, the cost would be the cost of land, and the cost of planting: each tonne of CO_2 would require 50 m^2. I imagine that preparing one square metre, planting a sapling in it, and maintaining that square metre for the first year while the sapling matures, might cost about £5 at UK wages? So labour costs of planting might be £250 per tonne of CO_2.

Find out the cost of running the forestry commission; find out the cost of a hectare of green belt land.

Farm land costs about £4000 per acre – that's about £1 per m^2. So £50 per tonne of CO_2.

Putting together the cost of the land and the cost of planting, I estimate £300 per tonne of CO_2 ($550).

McKinsey

According to McKinsey, if society behaved rationally, plucking all the low-hanging fruit, the easy changes that reduce CO_2 pollution, ranked from cheapest to more expensive, a satisfactory reduction in CO_2 pollution (satisfactory-for-450 ppm) would be achieved once the cost reached about €40 per tonne of $CO_2^{(e)}$. Satisfactory means "a reduction of 26 $GtCO_2^{(e)}$ per year in 2030, compatible with stabilization at 450 ppm." They emphasize, however, that half of these potential abatements would be in developing economies.

Costs projected by seers

Another sort of number: not the price of a permit, but the cost to society of reducing pollution, or the cost to society of *not* reducing pollution. In the 2003 White Paper 'Our Energy Future', the UK government estimates the cost of reducing CO_2 pollution by 60% by 2050 to be £55–82 per tonne of CO_2 ($100–150). The Oxford Environmental Change Institute estimates that the true cost to society per tonne of CO_2 is about £200. The Stern review estimates that the social cost of carbon pollution *today*, if we remain on a business-as-usual trajectory, is of the order of $85 per tonne of CO_2. In the future, they project that the social cost of carbon pollution would become higher.

Barker et al. [2006] predict that if sales taxes (in the USA) and value added tax (in the EU) were reduced and replaced by a carbon tax then a target of 450 ppm CO_2could be reached if the carbon price rose (by 2050) to $110 per ton of CO_2; moreover this carbon price would stimulate innovation and lead to enhanced economic growth and higher incomes.

A shift in taxes

The current tax system is blind to carbon. VAT taxes the value-adding-chain in just the same way whether the chain is guzzling carbon or not. (In fact to be precise, there are a few cases such as home heating and air travel, both carbon-intensive services, where the tax rates are different. But that's a detail.)

If we are aiming to achieve a 60% or 90% turn-around in the way we get and use energy, surely it makes sense to consider making a 90% turn-around in the way we collect taxes from ourselves?

Instead of viewing carbon taxes as a small add-on, how about eliminating most of the carbon-insensitive taxes, and replacing them with a new carbon-based tax? The carbon tax could be applied at the point of entry of the carbon to our economic area: tax the oil as it is unloaded from ships, the gas as the pipelines cross our borders, and the coal when we dig it out of the ground. Only a very small number of organizations would need to be troubled with this new tax system; and they would pass the cost of the carbon on through the normal economic channels. To reduce the side-effect of carbon-intensive activities simply being exported to countries outside the carbon-border, there would be two options:

1. Persuade as many countries as possible to come inside a common carbon border.

2. Where carbon-intensive goods are imported from countries outside our carbon border, apply an appropriate tax roughly proportional to the estimated 'embodied carbon' in the goods. (Covering raw materials, manufacture, and transport outside the carbon-border.) For simplicity, this tax could be proportional to the weight of the goods, including their packaging. A crude approximation, but one with various useful side-effects.

The elimination of the VAT system would have significant benefits for small businesses, who would have to do less administration.

OK, let's find an interesting number. How big would the cost of CO_2 need to be, such that the carbon tax revenues in the UK would equal current government tax revenues? VAT was £74 billion per year in 2004–5. Total government expenditure is roughly £360 billion. The UK's total CO_2 pollution is intended to be about 550 million tons of CO_2 per year in 2010, if we are on target for a 60% reduction by 2050. To replace VAT, carbon taxes would need to be

$$\frac{\text{£74 billion}}{\text{550 million tons}} = \text{£}135 \text{ per ton} \simeq \$250 \text{ per ton.}$$

To produce revenue equal to total taxation, carbon taxes would need to be

$$\frac{\text{£360 billion}}{\text{550 million tons}} \simeq \text{£}1200 \text{ per ton} \simeq \$650 \text{ per ton.}$$

If carbon consumption gradually decreased, so the price of CO_2 required to keep revenue constant would increase. At 2050's target level, for example, the price of CO_2 required to replace VAT would be about \$550 per ton, and to replace all taxes, about \$2700 per ton.

Closing thoughts

Energy is astoundingly cheap today. Electricity is so cheap that even if it cost 1000 times as much we would still buy it. To prove this, look at the price we pay for a standard battery to power a torch, palm-top game, radio or clock. One AA battery delivers an energy of about 0.004 kWh, and people happily buy them for a pound, which corresponds to a price of £250 per kWh, more than a thousand times the price of domestic electricity.

Notes

51 The European Commission 'over-allocated emission rights for the first three years of the scheme'. *Nature* editorial, volume 441, page 384, 25th May 2006.

52 An example of an eminent politician whose energy policies seem strangely short-termist is Gordon Brown. On Saturday 10th September 2005, Gordon Brown (then Chancellor) said the high price of fuel posed a significant risk to the European economy and to global growth, and urged OPEC to raise oil production [b7qz8]. Now, just as sure as one plus one is two, increased production means increased CO_2 emissions. But even though environmental campaigners pointed out that high fuel prices are "exactly what we *need* to help us get off our addiction to oil", Gordie said it again six months later: 'we need ... more production, more drilling, ... more petrochemical investment'. (April 22 2006) [y98ys5]

56 Aid budget for Africa – source: Der Spiegel. USA's imports from Africa, and Africa's GDP – source: wikipedia.

55 IF THE COST OF CO_2 POLLUTION IS REALLY GOING TO REDUCE AIR TRAVEL SIGNIFICANTLY, I GUESS THE PRICE WOULD HAVE TO BE ABOUT £400 PER TONNE ($700).
My analysis of the response of the marketplace is terribly simplistic, but my rough estimates, based on the idea of price-doubling, seem to be backed up by the more careful analysis of real economists. For example, A 2007 report by the Tyndall Centre [Anderson et al., 2007] "suggests that even a price of €300 per tonne would bring only a moderate increase in ticket prices and a moderate fall in passenger numbers." [3dg9ar]

Notes

CO_2 emission permit cost: If aim for 450ppm, then $350 per tonne C If aim for 500ppm, then $125 per tonne C

Source: fig 38.5 in the Cambridge avoid-dang book; UK Tyndall centre and Cambridge Econometrics.

October 2006 Postnote Number 268 CARBON FOOTPRINT OF ELECTRICITY GENERATION Parliamentary Office of Science and Technology http://www.parliament.uk/parliamentary_offices/post/new.cfm [2bedpf]

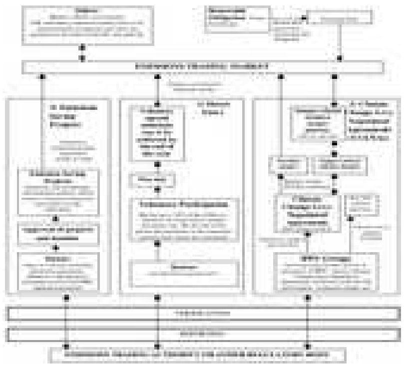


Figure 6.2. Keep it simple, stupid. An overview of the mechanisms for UK emissions trading (from Mott MacDonald 2001). Emissions trading schemes include the Direct Entry trading scheme, Climate Change Levy Negotiated Agreements (with either absolute or relative targets), and Emission Saving Projects; oh, and don't forget Renewable Obligation Green Certificates. One consequence of this mechanism is that 'electricity generators are unable to participate in the non-project arena of the ETS because the emissions from the electricity generators have been allocated downstream'. All clear?

Notes

Typical UK CO_2 emissions

The breakdown is much the same as it was for energy.

House. 6t/y. 2.5 people. (so 2.5t per person in house.) Travel. about 2.5t average (mainly for car drivers) Food. 2.9t/y. Tractors, fertilizer, pesticides, processing, packaging, transport, cooking, throwing away. Organic food is 30% better (as long as it is local). Everything you spend money on. Government doing stuff for us with our taxes – roads, bombs, etc. 2.4t/y.

> "The European Trading Scheme could become a messy and deeply flawed market for a virtual commodity that only really benefits the traders"

Power source	Carbon footprint (g $CO_2^{(e)}$/kWh)
Coal	1000
Coal with CCS (unproven)	130
Gas	500
Gas with CCS (unproven)	250
Biomass – low-density miscanthus	93
Biomass – high-density wood chips	25
Photovoltaics in the UK	58
Photovoltaics in a sunny place	35
Wave and tide	25–50
Onshore wind	4.6
Offshore wind	5.3
Nuclear at present	5
Nuclear in the future, using low grade uranium	7
Hydroelectric storage	10–30
Hydroelectric run of river	5

Table 6.3. Life-cycle assessment of electricity generation technologies. Don't forget to include leaks from gas. Biomass with CCS could offer negative emissions – up to 410 g per kWh in principle – but there is a scale problem: biomass is expected only ever be a small power contributor (50 MW stations maximum), and CCS facilities are expected to be adopted only at big power stations.

World Wildlife Fund

Global and EU cumulative carbon budgets

In scenarios called '450 low' and '450 high' (I think these are both carbon-only figures), 1990–2100: Global – 1430-2260 GtCO_2. Of which the EU's share (apportioned under the 'contraction and convergence' system) is 160–210 GtCO_2. Expressed as an average rate of emissions shared among 500 million people, the EU figure is 2.9–3.8 tons per year per person. The global figure is 2.2–3.4 tons per year per person.

Mythconceptions

'To reduce your carbon emissions, switch to a green electricity provider'.

I'm amazed that organizations such as `cred` promote this looney idea. *If* the price charged by green providers were significantly higher than fossil-electricity, *then* increasing the demand for expensive green electricity might be a good idea – helping them sell something they couldn't otherwise sell, and giving extra cash for investment in more green power. But, as most of the providers emphasize when trying to recruit customers, they *don't* charge significantly more for their green energy. (One exception in the UK at present is 'Good Energy', who do charge more.) And regardless of whether green electricity costs the same or more, what happens when Joan takes `cred`'s advice and switches from

BrownGoop Corp. to GreenAir, Inc.? Elementary economics predicts that the price of BrownGoop's electricity will drop very slightly, and Ivan (Joan's next-door neighbour, who cares not a bit from whom he buys his energy) will feel very content that he buys all his power from BrownGoop.

Switching electricity provider is a bureaucratic charade that does as much good as rearranging deck-chairs on the Titanic.

In the UK, there is a bureaucratic complication called the renewables obligation: the government has created a market in which certain organizations are obliged by law to buy some 'green' electricity. So if keen individuals go and buy up all the green stuff first, those organizations will be obliged to invest in new green sources. I still feel sceptical, however: surely if a shortage of green electricity were induced in this way, the price of green electricity would rise significantly, and then most people wouldn't feel happy with the switch to the green provider.

In fact, the bureaucratic complications only serve to give the crooked more ways to milk the gullible. Here's my understanding of the way ROCs (renewables obligation certificates) are used in the world of green power. ROCs were introduced as a way of forcing the power community to build more green power. When a green source produces some electricity it can sell that electricity to customers on the grid who want electricity; and in addition a proportionate quantity of ROCs land in its pocket, and it can sell those too, to people – usually big brown power companies – who want ROCs. The big browns are obliged by law to collect a load of ROCs proportional to the amount of electricity they sell. They can do this either by putting up green windmills and holding onto the ROCs, or by buying ROCs from other people who have them to spare, thus avoiding the need to put up new windmills.

Summary: If you want to buy "green" electricity in a way that actually makes a difference (i.e., that causes more green electricity to be produced, and less brown), then you should not only pay the provider for the green electricity but should ensure that they retire *all* the ROCs associated with that electricity (that is, not sell them to anyone). Otherwise, if they don't retire the ROCs, they'll be sold on the ROC market to another brown organization, who will use the ROCs to avoid having to put up new green power sources; indeed, your resold ROCs will probably be used by that brown organization as green tokens, to justify their own "sale" to the undiscerning customer of "green electricity". In this way, *one piece of green electricity gets sold twice*, once to you, and once to some other schmuck.

Notes

62 GREEN PROVIDERS . . . *don't* CHARGE SIGNIFICANTLY MORE FOR THEIR GREEN ENERGY. For example, Ecotricity "guarantees to match the standard price of every regional supplier in the UK . . . so switching to green energy needn't cost more. Something Ecotricity calls 'green for the price of brown'." [yr4ylg]

7

Carbon engineering

From Socolow...

... To achieve dramatic reductions in carbon emissions over the next half-century, one must be vigilant about today's long-lived capital investments. ... (page 366)

A wedge of wind power can arise from either **two** million one-megawatt windmills backing out efficient coal power plants or **four** million one-megawatt windmills making hydrogen for cars and backing out efficient gasoline cars. Thus, from a climate perspective, in most parts of the world, the optimal use of nuclear energy, hydro-energy (falling water), wind or wave energy, solar thermal energy, geo- thermal energy, and photovoltaic energy, will be to provide electricity, as long as coal power (without CO2 capture and storage) is still around. There will, of course, be special situations, such as Iceland, where the case for electrolytic hydrogen as a carbon emission reduction strategy may be compelling. A wedge of nuclear power is its displacement of 700 modern 1000-megawatt coal plants. Today's stock of nuclear power plants is about half this large. Thus, if, over the next 50 years, today's global fleet of nuclear power plants were to be phased out in favor of modern coal plants, about half a wedge of additional CO2 emissions reductions would be required

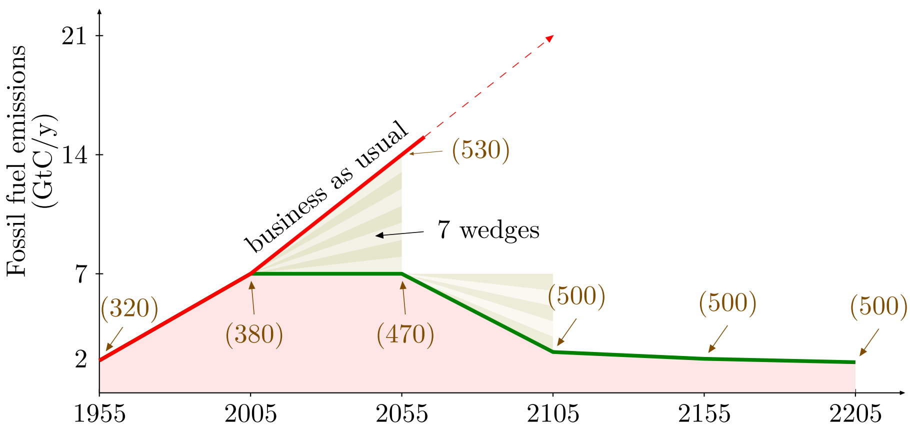


Figure 7.1. Socolow wedges

to compensate. This half-wedge would not be required if current nuclear reactors were replaced with new ones, one–for–one.

	Option	Effort by 2055 for one wedge relative to business as usual
ENERGY EFFICIENCY AND CONSERVATION		
1.	Efficient vehicles	Increase fuel economy for 2 billion cars from 30 to 60 mpg
2.	Reduced use of vehicles (Urban design, mass transit, telecommuting)	Decrease car travel for 2 billion 30-mpg cars from 10,000 to 5,000 miles per year
3.	Efficient buildings	Cut carbon emissions by one-fourth in buildings and appliances projected for 2055
4.	Efficient baseload coal plants	Produce twice today's coal power output at 60% instead of 40% efficiency (compared with 32% today)
FUEL SHIFT		
5.	Gas baseload power for coal baseload power	Replace 1400 GW 50%-efficient coal plants with gas plants (4 times the current production of gas-based power)
CO_2 CAPTURE AND STORAGE		
6.	Capture CO_2 at baseload power plant	Introduce CCS at 800 GW coal or 1600 GW natural gas
7.	Capture CO_2 at H_2 plant	Introduce CCS at plants producing 250 MtH_2/year from coal or 500 MtH_2/year from natural gas (compared with 40 MtH_2/year today from all sources)
8.	Capture CO_2 at coal-to-synfuels plant	Introduce CCS at synfuels plants producing 30 million barrels per day from coal, if half of feedstock carbon is available for capture
NUCLEAR FISSION		
9.	Nuclear power for coal power	Add 700 GW (twice the current capacity)
RENEWABLE ELECTRICITY AND FUELS		
10.	Wind power for coal power	Add 2 million 1-MW-peak windmills (50 times the current capacity) 'occupying' 30 10^6 ha, on land or off shore
11.	PV power for coal power	Add 2000 GW-peak PV (700 times the current capacity) on 2×10^6 ha
12.	Wind H_2 in fuel-cell car for gasoline in hybrid	Add 4 million 1-MW-peak windmills (100 times the current capacity)
13.	Biomass fuel for fossil fuel	Add 100 times the current Brazil or U.S. ethanol production, with the use of 250×10^6 ha (1/6 of world cropland)
FORESTS AND AGRICULTURAL SOILS		
14.	Reduced deforestation, plus reforestation, afforestation and new plantations.	Decrease tropical deforestation to zero instead of 0.5 GtC/year, and establish 300 Mha of new tree plantations (twice the current rate)
15.	Conservation tillage	Apply to all cropland (10 times the current usage)

Table 7.2. Potential wedges: Strategies available to reduce the carbon emission rate in 2055 by 1 GtC/year, or to reduce carbon emissions from 2005 to 2055 by 25 GtC. From Socolow 2006.

8

The last thing we should talk about

Capturing carbon dioxide from thin air is the last thing we should talk about.

Pumping carbon out of the ground is big bucks. In the future, assuming that inadequate action is taken now, pumping carbon into the ground is going to be big bucks.

What's the best way to suck CO_2 from thin air?

By the laws of physics, Energy cost $\geq$ 0.7 kWh per kg of CO_2.

Looking at the literature, Energy cost 3.3 kWh per tonne. Plausible cost: $140 per ton of CO_2

At $90/barrel, the oil industry turns overs $2.5 trillion/y. Each barrel = 0.4 tCO_2, so at $90/barrel, people pay $225 to emit 1 ton CO_2.

1700 kWh per barrel, so oil costs 5.4 c per kWh.

What's going to happen

At some point in the future, a coalition of the willing will agree to clean up everyone's mess.

0.03% CO_2 $\longrightarrow$ Pure CO_2 $\longrightarrow$ Liquid CO_2

Keith et al. [2005]

33 Gt per year sequestration from thin air, at 100*perton* :3.3 trillion per year Additional power required: 12 TW (cf world consumption = 15 TW today)

Technologies

Amines?

CaOH?

Trees?

Algae?

Pumping water up from mid-ocean?

Lifetimes.tex

Lifetimes of greenhouse gases

CO2 50 years according to a glib slide. 5-500 according to another page IIRC.

In the case of a CH4 addition, the longest-lived mode has an e-fold time of 12 years, close to the perturbation lifetime (PT) of CH4, and carries most of the added burden.

Great webpages!

curses, this page does not talk abotu CO2!!!

Modelled ocean-atmosphere flux during 1980 to 1989 was in the range -1.5 to -2.2 PgC/yr for the 1980s, consistent with earlier model estimates and consistent with the atmospheric budget. Modelled land-atmosphere flux during 1980 to 1989 was in the range -0.3 to -1.5 PgC/yr, consistent with or slightly more negative than the land-atmosphere flux as indicated by the atmospheric budget. CO2 fertilisation and anthropogenic N deposition effects contributed significantly: their combined effect was estimated as -1.5 to -3.1 PgC/yr. Effects of climate change during the 1980s were small, and of uncertain sign. In future projections with ocean models, driven by CO2 concentrations derived from the IS92a scenario (for illustration and comparison with earlier work), ocean uptake becomes progressively larger towards the end of the century, but represents a smaller fraction of emissions than today. When climate change feedbacks are included, ocean uptake becomes less in all models, when compared with the situation without climate feedbacks. In analogous projections with terrestrial models, the rate of uptake by the land due to CO2 fertilisation increases until mid-century, but the models project smaller increases, or no increase, after that time. When climate change feedbacks are included, land uptake becomes less in all models, when compared with the situation without climate feedbacks. Some models have shown a rapid decline in carbon uptake after the mid-century.

THIS IS GOOD:

There is sufficient uptake capacity in the ocean to incorporate 70 to 80% of foreseeable anthropogenic CO2 emissions to the atmosphere, this process takes centuries due to the rate of ocean mixing. As a result, even several centuries after emissions occurred, about a quarter of the increase in concentration caused by these emissions is still present in the atmosphere. CO2 stabilisation at 450, 650 or 1,000 ppm would require global anthropogenic CO2 emissions to drop below 1990 levels, within a few decades, about a century, or about two centuries respectively, and continue to steadily decrease thereafter. Stabilisation requires that net anthropogenic CO2 emissions ultimately decline to the level of persistent natural land and ocean sinks, which are expected to be small (¡0.2 PgC/yr).

I suppose one way to estimate it is to ask what is the rate of EMISSION of CO2 by geology. (eg volcanoes) This must balance, on average, the natural rate of deposit of CO2 into geology.

The amount that is ?fixed? from the atmosphere, i.e., converted from

CO_2 to carbohydrate during photosynthesis, is known as gross primary production (GPP). Terrestrial GPP has been estimated as about 120 PgC/yr based on 18O measurements of atmospheric CO_2 (Ciais et al., 1997). This is also the approximate value necessary to support observed plant growth, assuming that about half of GPP is incorporated into new plant tissues such as leaves, roots and wood, and the other half is converted back to atmospheric CO_2 by autotrophic respiration (respiration by plant tissues) (Lloyd and Farquhar, 1996; Waring et al., 1998).

Annual plant growth is the difference between photo-synthesis and autotrophic respiration, and is referred to as net primary production (NPP). NPP has been measured in all major ecosystem types by sequential harvesting or by measuring plant biomass (Hall et al., 1993). Global terrestrial NPP has been estimated at about 60 PgC/yr through integration of field measurements (Table 3.2) (Atjay et al., 1979; Saugier and Roy, 2001). Estimates from remote sensing and atmospheric CO_2 data (Ruimy et al., 1994; Knorr and Heimann, 1995) concur with this value, although there are large uncertainties in all methods. Eventually, virtually all of the carbon fixed in NPP is returned to the atmospheric CO_2 pool through two processes: heterotrophic respiration (Rh) by decomposers (bacteria and fungi feeding on dead tissue and exudates) and herbivores; and combustion in natural or human-set fires (Figure 3.1d).

HMM, looks like I estimated the CO_2 location wrong.

The total amount of carbon in the ocean is about 50 times greater than the amount in the atmosphere, and is exchanged with the atmosphere on a time-scale of several hundred years. Dissolution in the oceans provides a large sink for anthropogenic CO_2, due in part to its high solubility, but above all because of its dissociation into ions and interactions with sea water constituents (see Box 3.3). CO_2 that dissolves in seawater is found in three main forms. The sum of these forms constitutes dissolved inorganic carbon (DIC). The three forms are: (1) dissolved CO_2 (non-ionic, about 1% of the total) which can be exchanged with the atmosphere until the partial pressure in surface water and air are equal, (2) bicarbonate ion (HCO_3^-, about 91%); and (3) carbonate ion (CO_3^{2-}, about 8%).

the overall ability of surface sea water to take up CO_2 decreases at higher atmospheric CO_2 levels. The effect is large. For a 100 ppm increase in atmospheric CO_2 above today?s level (i.e., from 370 to 470 ppm) the DIC concentration increase of surface sea water is already about 40% smaller than would have been caused by a similar 100 ppm increase relative to pre-industrial levels (i.e., from 280 to 380 ppm). The contemporary DIC increase is about 60% greater than would result if atmospheric CO_2 were to increase from 750 to 850 ppm.

The uptake capacity for CO_2 also varies significantly due to additional factors, most importantly seawater temperature, salinity and alkalinity (the latter being a measurable quantity approximately equal to $[HCO_3^-] + 2 \times [CO_3^{2-}]$). Alkalinity is influenced primarily by the cycle of CaCO3 formation (in shells and corals) and dissolution (see Figure 3.1c).

Marine organisms also form shells of solid calcium carbonate (CaCO3) that sink vertically or accumulate in sediments, coral reefs and sands. This process depletes surface CO32-, reduces alkalinity, and tends to increase pCO2 and drive more outgassing of CO2 (see Box 3.3 and Figure 3.1). The effect of CaCO3 formation on surface water pCO2 and air-sea fluxes is therefore counter to the effect of organic carbon production.

THIS IS CRUCIAL!

Milliman (1993) estimated a global production of CaCO3 of 0.7 PgC/yr, with roughly equivalent amounts produced in shallow water and surface waters of the deep ocean. Of this total, approximately 60% accumulates in sediments. The rest re-dissolves either in the water column or within the sediment. An estimate of CaCO3 flux analogous to the export production of organic carbon, however, should include sinking out of the upper layers of the open ocean, net accumulation in shallow sediments and reefs, and export of material from shallow systems into deep sea environments.

Based on Milliman?s (1993) budget, this quantity is about 0.6 PgC/yr (? 25 to 50% at least).

HERE WE ARE!

Atmospheric CO2 concentration has varied on all time-scales during the Earth?s history (Figure 3.2). There is evidence for very high CO2 concentrations (¿3,000 ppm) between 600 and 400 Myr BP and between 200 and 150 Myr BP (Figure 3.2f). On long time-scales, atmospheric CO2 content is determined by the balance among geochemical processes including organic carbon burial in sediments, silicate rock weathering, and vulcanism (Berner, 1993, 1997). In particular, terrestrial vegetation has enhanced the rate of silicate weathering, which consumes CO2 while releasing base cations that end up in the ocean. Subsequent deep-sea burial of Ca and Mg (as carbonates, for example CaCO3) in the shells of marine organisms removes CO2. The net effect of slight imbalances in the carbon cycle over tens to hundreds of millions of years has been to reduce atmospheric CO2. The rates of these processes are extremely slow, hence they are of limited relevance to the atmospheric CO2 response to emissions over the next hundred years.

VULCANISM AND WEATHERING AND BURIAL

0.1, 0.2, 0.2 respectively.

cf fossil fuel burning is 5.3.

Need reservoir sizes too:

Ocean is 38,000.

Need to know how much faster sedimentation and burial changes when CO2 levels increased. Assume prop to ocean conc?

9

Carbon II

More graphs of CO_2 pollution

Figures 1.5–1.7 showed total greenhouse gas emissions in 2000 by region and country. Here are the equivalent graphs for CO_2 alone.

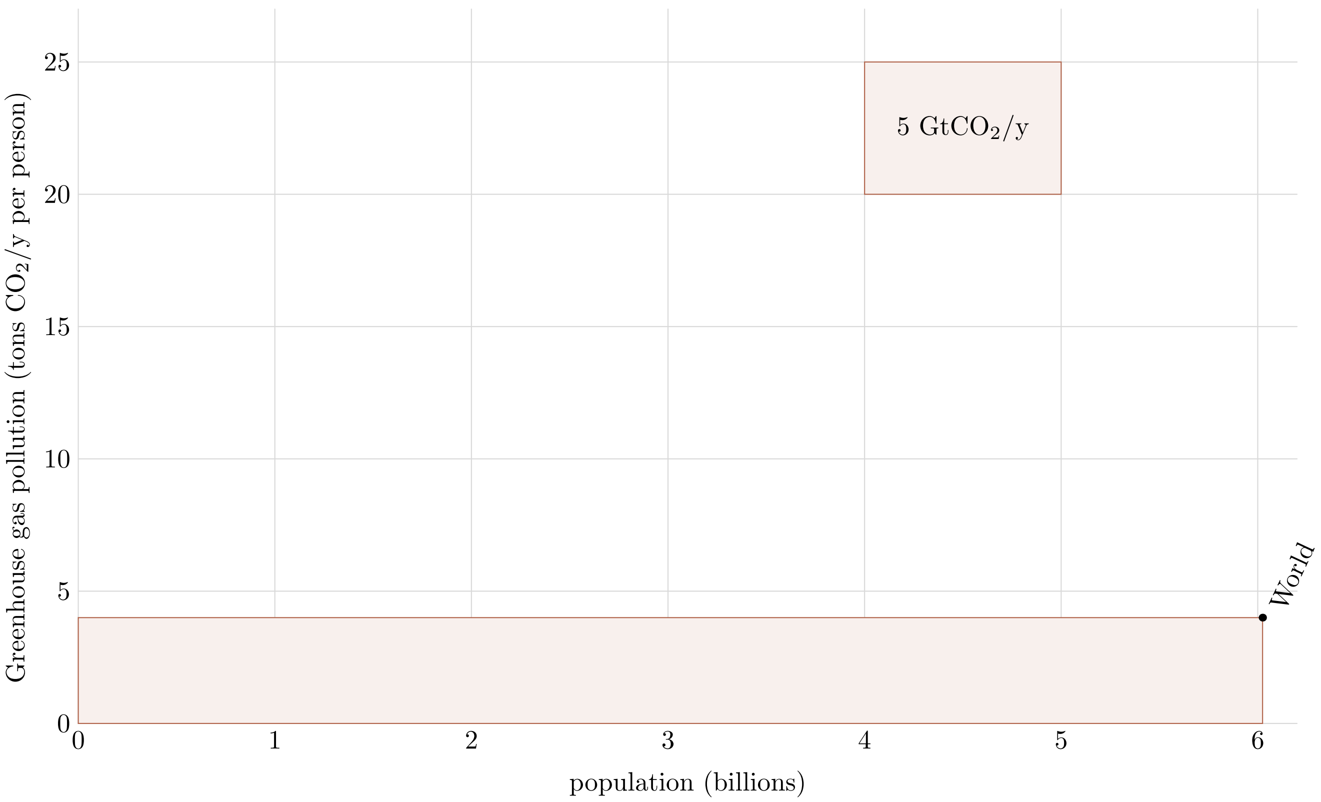


Figure 9.1. Total CO_2 emissions, $2000 = 24\,GtCO_2^{(e)}$

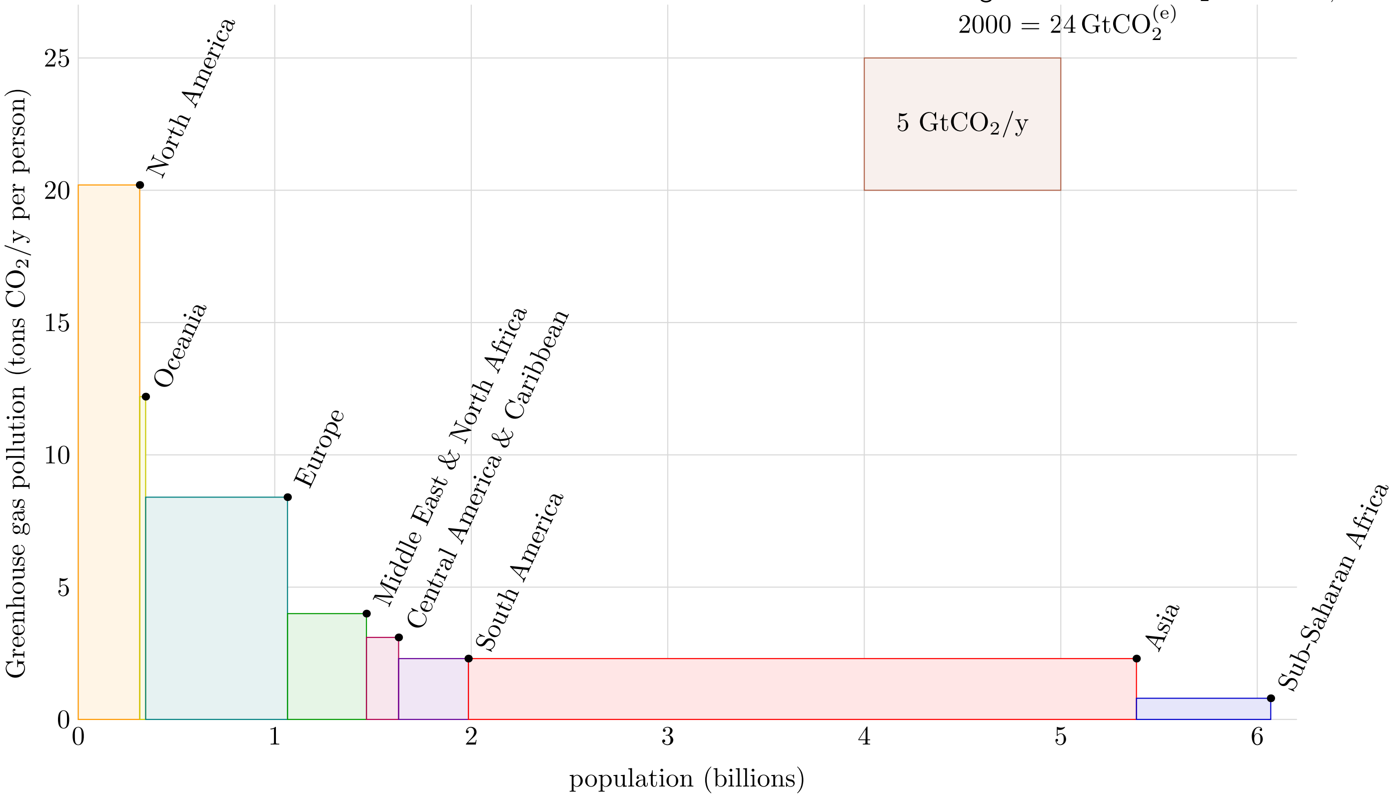


Figure 9.2. Breakdown of world CO_2 emissions by region.

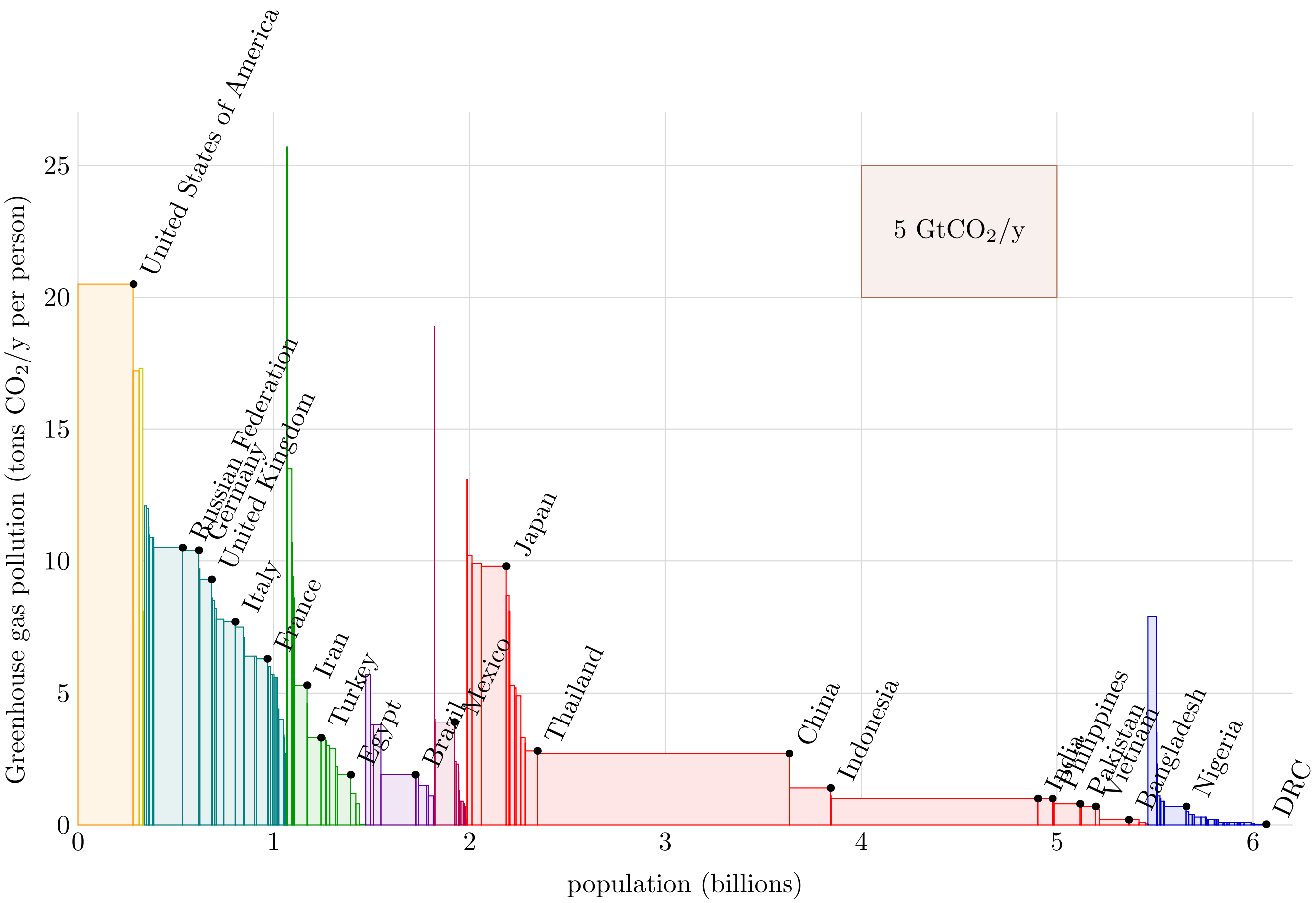


Figure 9.3. Breakdown of world CO_2 emissions by country.

10

Sequestration II

Some important facts about Sequestration

What's the energy cost of sequestration? Let's start by discussing sequestration from thin air.

If we change the concentration of CO_2 from 0.03% to 100%, the ideal concentration machine does work $kT \ln \rho_1/\rho_0 = kT \ln 3000 = 8kT$ per molecule. That's the cost of separating CO_2 out in gas form. If additionally we wish to compress the CO_2 into liquid form, we need to compress it by a factor of about 1000. This increases the energy cost by another $kT \ln 1000 \simeq 7kT$

kT per molecule is the same as 2.5 kJ per mol, so $15kT$ per molecule is 37 kJ/mol which is about 850 kJ/kg of CO_2, or 0.24 kWh per kg.

Compare this with the energy created when that kg of CO_2 is *created*: one kg of oil yields about 12 kWh of energy and generates about 3 kg of CO_2. So we get about **4 units per kg of CO_2**. If perfectly efficient.

Conversion factors			
Burning fossil fuels:	4 kWh	↔	1 kg of CO_2
Burning fossil fuels:	1 kWh	↔	0.25 kg of CO_2
Gas power station:	1 kWh(e)	↔	0.5 kg of CO_2
Coal power station:	1 kWh(e)	↔	1 kg of CO_2

Now be realistic. If an oil-driven engine drives a real compressor, the engine is perhaps 25% efficient, and the compressor the same: so get 1 unit per kg, and require $4 \times 0.24 \simeq 1$ unit to do sequestration – pretty much all the energy!

So much better to leave the fossil fuels where they are.

Check with manufacturers of CO_2, what is the actual cost per kg.

Redo calculation with 33% efficiency.

Production:				
1 kg of CO_2	↔	4 kWh heat	↔ /3	1.3 kWh useful energy
Sequestration:				
1 kg of CO_2	↔	0.24 kWh ideal cost	↔ ×3	0.7 kWh actual cost

Taking 0.7 kWh per kg of CO_2, that's an estimated energy cost of 700 kWh per ton. If one kWh has a wholesale price of 5p (9¢), that's a cost of £35 ($65) per ton captured. If the wholesale price of one kWh rises to 8p (15¢), then 700 kWh per ton means $100 per ton.

11

Summary

Are we about to run out of fossil fuels? No. There are plenty of fossil fuels – especially coal – for the next generation or two. Enough to do serious damage to the climate.

Getting off fossil fuels, quick, is essential to reduce the risk of catastrophic damage. And with coal being so cheap and plentiful, getting off fossil fuels is going to be politically difficult.

One way to carry on living on coal is to burn it in power stations that do carbon capture and storage.

But don't forget that more than half of our fossil fuels are currently used in individual buildings and cars, where carbon capture doesn't seem to be an option.

Part II

Other topics

12

Presentation

> 'When *I* use a word,' Humpty Dumpty said in rather a scornful tone, 'it means just what I choose it to mean – neither more nor less.'
> 'The question is,' said Alice, 'whether you *can* make words mean so many different things.'
>
> *Lewis Carroll*

One of the problems facing us as we think through about energy policy is the set of tricks that advocates of one view or another will use to try to persuade the public.

Tricks that exploit the public's gullibility, irrationality, or innumeracy must be debunked. To help quick debunking, here is a list of the main species of tricks I found lurking in the undergrowth this week.

The mega-fallacy

Describing a quantity in inappropriate units in order to make it sound big or small.

Also known as the number-of-zeroes fallacy.

Such language seems to help people win arguments, but it rarely educates: few people really have a feel for the difference between a thousand, a million, and a billion, so few would discriminate between the two statements 'The waste paper buried each year could fill 103 448 double-decker buses' and 'The waste paper buried each year could fill 1 034 480 double-decker buses,' even though the second statement is conveying a volume ten times as great as the first.

It's especially easy to perpetuate mega-delusions when discussing energy because the Watt is such a piddling small unit of power, and seconds are so much smaller than years. Here's an example of a double-sighting – two mega-delusions in a single press release:

> Schools and youth groups could win a wind turbine worth over £1500 in Friends of the Earth's 'Shout about climate solutions 2006' competition, launched today (23 June 2006).

> The turbine, donated by Windsave Ltd, could generate approximately 1 MWh of power per year and save up to 163 hot air balloons of carbon dioxide emissions.

The hot air balloon! That's a unit I hadn't encountered before. It's easy to make amounts of gas sound big: just report their volumes rather than their masses. 1 kg of CO_2 per day? Hmm, that doesn't sound very big. Two hundred thousand litres of CO_2 per year? Ah, that's much better!

$2\,\text{g } CO_2 \leftrightarrow 1\,\text{litre}$

Table 12.1. Volume-to-mass conversion: every 44 g of CO_2 occupies 22 litres.

As for the mega-hero of this press release: when 'one megawatt-hour per year' steps back into the phone-box and takes off his coloured underpants, we discover that it is really only 120 W – the same as a couple of light-bulbs.

The famous mobile phone charger is another string-of-zeroes villain in 'making a difference' stories. 'Unplugging mobile phone chargers could save consumers £60m a year and cut CO_2 emissions by 250 000 tonnes', reports Hilary Osborne in the Guardian. Wow! Millions of pounds, and thousands of tonnes? Let's express the power wasted on mobile phone chargers as a fraction of total power consumption. Six hundred million kWh per year per UK works out to 0.03 kWh per day each, which is *one fiftieth of one per cent* of total energy consumption.

That last example also illustrates our next method for making misleading numbers.

The 'if-everyone' multiplication

Another way to make something *small* sound *big* is to say 'if *everyone* did X, then it would provide enough energy/water/gas to do **Y**', where Y of course sounds impressive. Is it surprising that Y sounds big? We got Y by multiplying X by the number of people involved – 60 million or so!

Here's an example from the Conservative Party's otherwise straight-talking *Blueprint for a Green Economy*:

> "The mobile phone charger averages around . . . 1 W consumption, but if every one of the country's 25 million mobile phones chargers were left plugged in and switched on they would consume enough electricity (219 GWh) to power 66 000 homes for one year."

66 000? Wow, what a lot!

But let me put this another way:

> If you leave your mobile phone charger plugged in, it uses one quarter of one percent of your home's electricity.
>
> If *everyone* leaves their mobile phone charger plugged in, they'll use one quarter of one percent of their homes' electricity.

66 000 sounds a lot, but it is (of course, inevitably) just one quarter of one percent of 25 million.

This 'if-everyone' multiplication is a *bad thing* because it deflects people's towards 25 million minnows instead of 25 million sharks.

The bogus comparison

Comparing something with something inappropriate in order to make it sound big or small.

Bush on oil imports is an interesting example.

George Bush, speaking in Nashville, said the US was close to a breakthrough in making ethanol from materials like grasses or woods. He proposed replacing "more than 75% of our oil imports from the Middle East by 2025", making "our dependence on Middle Eastern oil a thing of the past."

The goal is not quite as ambitious as it might sound. These days the US gets more oil and petroleum products from Venezuela, Mexico and Canada than it does from the Middle East.

The missing comparison

Quoting a quantity without comparing it with something it really ought to be compared with. Often found consorting with the mega-fallacy.

Example from BP's website, describing how BP is 'helping to reduce emissions of CO_2 by improving vehicle efficiency':

> 'A study in India estimated that the use of BP's multigrade lubricants by heavy goods vehicles in India reduced emissions by 0.8 million tonnes CO_2 per year'

Wow, 0.8 *million*, what a lot! But if we are to know whether this is indeed evidence of helpful reduction in CO_2 emissions, as claimed, we need to know how this reduction *compares* with the total. If a reduction of 0.8 million represented a halving of CO_2 emissions, that would be something worth emailing home about. But if BP's wonderful lubricants are only reducing emissions by 1%, then this '0.8 million' boast is just corporate poppycock. Yes, a 1% reduction is 'better than nothing'. But remember, most climate scientists and (I think) BP agree that we urgently need to reduce CO_2 emissions by 60–80% (see chapter 1). 1% is 'better than nothing'; and bailing the sinking Titanic with a teaspoon is better than nothing, too; but boasting to the passengers about your wonderful teaspoon shows a lack of respect.

The irrelevant comparison

'More energy is used by phone-chargers left plugged in than is used for actually charging phones'. Irrelevant because the amount used for 'actually charging phones' is itself tiny.

What we need is a comparison with total energy consumption. A typical idle mobile phone charger uses less than half a watt. The average person's total energy consumption of 120 kWh per day can also be expressed as 5000 W. So keeping one charger switched off saves *one hundredth of one per cent* of total consumption. In financial terms, it saves about 50p per year. Some older phone chargers consume more – perhaps 3 W. Leaving such a charger on consumes one tenth of one per cent of total power, and costs about £3 per year.

Would be good to find out what the energy cost of making the phone is. If a phone costs 100 kWh to make (no source for this yet! I just took the PC figure divided by 25.) and is replaced every 18 months, it costs 0.18 kWh per day, or 8 W. Much more than leaving the charger on.

Speaking with many faces

A particularly tricky fallacy to deal with: saying one thing, then saying another that contradicts it.

Gordon Brown, on the 22nd of April 2006, was asked whether Climate Change is a moral issue. Yes, he said. And on the same day, he said 'we need more oil extraction'.

Tony Blair, whose government introduced the radical policy of a 60% reduction in CO_2 emissions also said (Wed Jan 10 2007) he would not give up flying, doubted any politician would tell people not to fly, and questioned the impact of UK-only climate action [yg6swy].

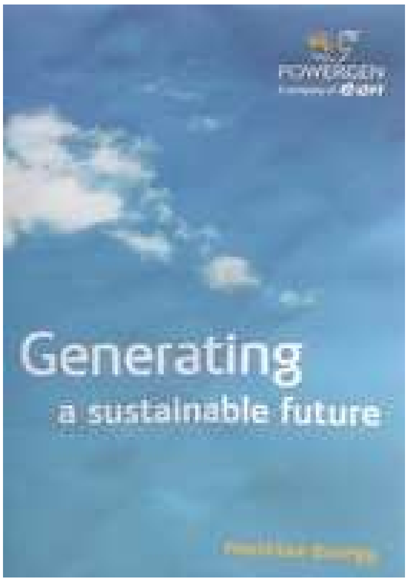


Figure 12.2. Powergen – A company of E.ON, selling electricity and gas – sent this reassuring leaflet to their electricity customers. Their energy is 'positive', and they are 'generating a sustainable future'. So that's all right then!

Double-speak

By double-speak, I mean the bold appropriation of words. Double-speak is used to label things that might objectively be called 'bad' as 'good'. Peacemaker missiles.

In the energy world, anything can be labelled 'low-energy' or 'zero-carbon'. The truth is unrelated to the name. For example, a new city planned in China is called 'Zero-Carbon city Dong Teng' (CHECK). But a presentation by consultants involved in designing the city made clear that the city will actually consume fossil fuels just like any other city. If all goes well, the carbon emissions might be about one third those of a standard city. I applaud this innovation, but I deplore the hijacking of the word zero. We really do need 'zero-carbon' technologies, and if the word 'zero' actually just means whatever the Red Queen wants it to, rational discussion of this topic will become increasingly difficult.

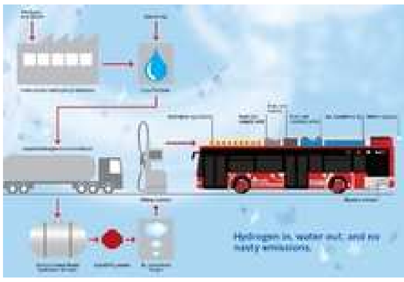


Figure 12.3. 'Hydrogen in, water out, and no nasty emissions' – an example of a bold redefinition of words (in this case, either the word 'emissions', or the word 'no'). The top of the diagram shows methane and steam being used to generate hydrogen, and electricity being used to liquify the hydrogen, all without any nasty emissions.

Amazingly, in California, legislators have defined a 'zero-energy building' to be 'a building that uses 40% less than the norm'. I wonder if the legislators have a 'zero-drugs' policy too?

The word 'sustainable' has also been hijacked (figure 12.2). I'm not saying Powergen are especially evil; indeed they have given me some nice free low-energy lightbulbs. But their leaflet seems to me to assert that their electricity generation is 'sustainable'. Is electricity from coal- and gas-burning power stations 'sustainable' now? That's where most of Powergen's power still comes from. Only 2% of their electricity is from renewables!

The word 'green' has also been hijacked by Powergen. Advertisement Tue 24/7/07, Stevenage. `powergen.co.uk/greener` "Go greener with Powergen" Greener than what? According to `http://www.ukwatch.net/article/green_electricity`, Powergen is the company that supplies the least green electricity (that is, the lowest fraction) in the UK. The ASA is clamping down on the abuse of the word 'green' [`32ae8h`]

What about 'near-zero'? Honda's website asserts that the Honda Civic GX uses compressed natural gas 'to achieve near-zero emissions' `http://corporate.honda.com/environmentology/`. What does that mean? Well, to be precise, it's a Advanced Technology Partial Zero-Emission Vehicle (AT-PZEV). Clear now? What, you don't know the difference between an LEV, a ULEV, an SULEV, a PZEV, an AT PZEV and a ZEV? Let's start with examples of a LEV and a ULEV. The famous Honda Civic (1996) was 'the first gasoline Low-Emission Vehicle'; the Honda Ridgeline (2006) is 'an Ultra-Low-Emission Vehicle'. It has a 3.5 litre engine that generates 247 horsepower. It achieves 16 mpg in the city and 21 mpg on the highway. Mystifying – I was expecting that an Ultra-Low-Emission Vehicle would sound *better* than a 'Low-Emission Vehicle'; but this range – from 19 to 25 miles per UK gallon – doesn't sound very impressive. But yes, it's an 'ultra-low-emission vehicle' because an Ultra-Low Emissions Vehicle is a vehicle that has been verified by the California Air Resources Board `http://www.arb.ca.gov/` to emit 50% less polluting emissions than the average for new cars. 'Super Ultra Low Emission Vehicles' are 90% cleaner than the average new model year car. A 'partial-zero emission vehicle' is much the same as a 'Super Ultra Low Emission Vehicle'. Finally, a definition of zero: a 'zero-emission vehicle' has tailpipe emissions that are 98% cleaner than the average new vehicle. So 'zero' means 0.02. Splendid news. Until we learn that carbon dioxide is not considered an emission by the California Air Resources Board! In the California vehicle regulations, 'emissions' include smog-forming hydrocarbons, nitrogen oxide, and carbon monoxide; but not CO_2. I wonder whether other consumers suffer from the same confusion as me, thinking that a 'near-zero emissions vehicle' emits little CO_2 pollution.


CHINA'S GREEN LEAP FORWARD
ZERO-CARBON BECKTON COMMUNITY UNVEILED
Welcome to Ken's ultra-green London

Figure 12.4. Newspaper articles about 'zero-carbon' developments in China and London.

One reason for expecting such confusion to arise is that the CARB does use the word 'emissions' when discussing CO_2 pollution (eg, Climate Change Emission Control Regulations 'In September 2004 the California Air Resources Board approved regulations to reduce greenhouse gas emissions from new motor vehicles.' From `http://www.arb.ca.gov/html/fslist.htm`)

Here are the CO_2-equivalent standards which will come in in 2009:

201 g $CO_2^{(e)}$ per km (for passenger cars and small trucks/SUVs) and 273 g $CO_2^{(e)}$ per km for large trucks and SUVs. The standards will tighten gradually, reaching 127 g $CO_2^{(e)}$ per km (for passenger cars and small trucks/SUVs) and 206 g $CO_2^{(e)}$ per km for large trucks and SUVs in 2016. These figures (which I think describe the required *average* of the new fleet) can be compared with the histogram of fossil-fuelled cars currently for sale in the UK, figure **??**.

Zero in Britain

From Energy saving trust: `http://est.custhelp.com/`

What is a zero carbon home?

Answer

The energy used in our homes leads to carbon dioxide emissions as a result of the burning of fossil fuels (gas, coal etc) to generate the heat and electricity we use.

With 27 per cent of the UK's carbon dioxide emissions coming directly from the way we use energy in our homes, it has become increasingly important that every one of us undertakes measures to reduce our energy consumption.

The Government has set a target for all newbuild homes in England and Wales to be "zero carbon" by 2016. A home can be considered fully "zero carbon" when it results in no net emissions of carbon dioxide arising from the energy use within that home i.e. space heating, water heating, lighting, appliances.

Achieving a "zero carbon" standard is possible by employing a mix of house design improvements, energy saving measures and renewable technologies. These include:

Very high standards of insulation. Air tightness to avoid warm air leaking out. Attention to details and thermal bridges. Heat recovery ventilation returning the warmth from "waste air" back into the home. Renewable technologies, such as solar and wind. Energy saving recommended products, such as washing machines, dishwashers, televisions and lighting.

At the moment the additional cost of creating a "zero-carbon" home is around £35,000. However, this figure is set to drop dramatically over the next few years as energy saving measures and renewable technologies become main stream and the norm. We only need to look back at the cost of the first mobile phones or computers to see how much and quickly prices come down.

Do you feel this answer was an answer?

Low and Zero in advertising

The Lexus RX 400h is advertised with the slogan 'LOW POLLUTION. ZERO GUILT'. What are its actual pollution figures? Its fuel-efficiency is 34.9 miles per gallon (8.1 l/100 km) and its CO_2 emissions are 192 g/km. As you can see from figure **??**, this level of pollution is not very low, compared with all cars.

Thankfully some people are sticking up for the truthful use of the words 'low' and 'zero'. The advertising standards authority ruled that this advertisement breached the advertising codes on Truthfulness, Comparisons and Environmental claims. "We considered that ... readers were likely to understand [from the headline claim 'HIGH PERFORMANCE. LOW EMISSIONS. ZERO GUILT'] that the car caused little or no harm to the environment, which was not the case, and had low emissions in comparison with all cars, which was also not the case."

Every little helpsism

Edmund Burke said

> Nobody made a greater mistake than he who did nothing because he could only do a little.

But I say

> No, the greatest mistake is to believe that lots of people doing a little makes a lot of difference.
>
> or
>
> to put effort into getting people to do only a little. Or
>
> ... to believe that doing only a little makes a difference.

Here's a classic example of every-little-helpsism.

> "If 1% of the car owners in America left their cars idle for one day a week, it would save 42 million gallons of gas a year. Destructive emissions would be cut down commensurately; we'd keep some 840 million pounds of CO_2 out of the atmosphere, for instance."

Starting from a tiny action, huge consequences follow! But the simple fact is, if 1% of people avoid driving one seventh of their driving, the saved energy, expressed as a fraction of the total, rather than in impressive millions of this and that, is:

one seventh of one percent.

Good intentions gone awry

One of the most painful – people earnestly doing something that they believe is good for the planet in a way that makes things worse, on balance.

Example: driving twenty miles to take one glass bottle to a recycling centre.

The inflated difference

Comparing two things and declaring the better of the two to be 'green' or 'environment-friendly', even though the fractional difference between the two is tiny.

Examples:

- the Airbus super-jumbo is declared an environment-friendly plane, even though it is only 12% more efficient, in passenger-miles per litre, than a Boeing 747.
- When unleaded fuel was introduced across the UK, car owners were encouraged to display 'I've gone green' stickers while continuing to roar around just as much as before, killing cyclists, pedestrians, and themselves, belching out fumes and CO_2, and contributing to stinking congestion.
- 'Biodiesel' often contains as little as 20% biological fuel; the remaining 80% is fossil fuel. (Or less!) CHECK THIS.

Makes people feel better, salves their consciences.
Similar to the 'every little helps' fallacy.

> The current infatuation with biodiesel creates the dangerous illusion of having done something about the massive problems of climate change and resource depletion. It fools us into believing that we can continue our fascination with big cars and RVs while still maintaining a clean conscience.
>
> *Jeff Falen Lebanon, Oregon*

The magic playing-field

Switching the rules of comparison or assessment half-way through a discussion.

For example, the Sustainable Development Commission, when discussing nuclear power and wind power: wind power is praised because it could, if increased to its practical maximum in the UK, supply 80% of current *electricity* consumption. Then nuclear power is dismissed on the grounds that even if nuclear power production were doubled it would reduce *total* CO_2 *emissions* by only 8%.

A second example is provided by the Guardian's environment editor, summarising a report from the *Oxford Research Group*. Again the magic playing field is used to try to knock nuclear power: 'For nuclear power to make any significant contribution to a reduction in global carbon emissions in the next two generations, the industry would have to construct nearly 3,000 new reactors – or about one a week for 60 years. A civil nuclear construction and supply programme on this scale is a pipe dream, and completely unfeasible. The highest historic rate is 3.4 new reactors a year.' 3 000 sounds much bigger than 3.4, doesn't it! But this is a doubly-magic playing field, involving a switch not only of timescale but also of *region*. While the first figure (3,000 new reactors over 60 years) is the number required *for the whole planet*, the second figure (3.4 new reactors per year) is the maximum rate of building by a *single country* (France)!

The Guardian's reporter and the report's original authors should share the blame for this misleading comparison.

A more honest presentation would have kept the comparison on a per-planet basis. France has 59 of the world's 429 operating nuclear reactors, so it's plausible that the highest rate of reactor building for the whole planet was something like ten times France's, that is, 34 new reactors per year. And the required rate (3000 new reactors over 60 years) is 50 new reactors per year. So the assertion that 'civil nuclear construction on this scale is a pipe dream , and completely unfeasible' is poppycock. Yes, it's a big construction rate, but it's in the same ballpark as historical construction rates.

Are you not happy with my bold assertion that the world's maximum historical construction rate must have been about 34 new nuclear reactors per year? No problem. Let's look at the data. Figure 12.5 shows the power of the world's nuclear fleet as a function of time, showing only the power stations still operational in 2007. The rate of new build was biggest in 1984, and had a value of (drum-roll please. . .) about 30 GW per year. So there!

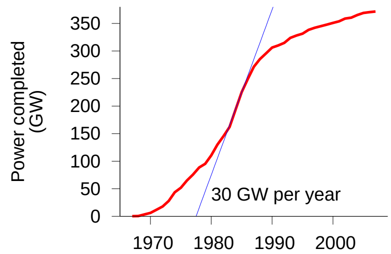


Figure 12.5. Graph of the total nuclear power in the world that was built since 1967 and that is still operational today. The world construction rate peaked at 30 GW of nuclear power per year in 1984.

Apples and Oranges

Similar to the magic playing field, but even more dishonest: comparing two quantities that are actually in completely different units, and thus not actually comparable at all. I haven't seen any examples of this recently, but an example would be to compare a one-off charitable donation with a country's GDP. A donation is an amount of money. A GDP is an amount of money per year. If we measured GDP per month or per decade, the numerical value of the GDP would change, but the value of the donation would not. Not a great example. Would like to find a better one, from the energy debate.

The irrelevant detail

One way to dismiss any argument is to say 'It's more complicated than that'. For example, when a Conservative politician was asked 'why didn't your leader David Cameron choose to drive a hybrid Prius (the most economical family car, average emissions 104 g CO_2 per km), instead of a V6 Lexus (also a hybrid, but with emissions of 184 g CO_2 per km)?', he responded 'ah, those average emissions figures assume a different mix of driving from David Cameron's: he does more long-distance driving, which means the Prius is not the most economical choice'. [Get exact quote.] Yes, the details of someone's driving habits do affect their precise consumption. But there is no way that a V6 Lexus will beat a Prius, at legal speeds!

Mixing up electricity and energy

"France's priority was to water down the renewables pledge to accommodate the fact that most of its energy is supplied by carbon-free nuclear power."

Fact: Of the 537 TWh of *electricity* France generated in 2003, 419 TWh were from nuclear. France's total energy consumption was 3300 TWh. So 13% of its energy is nuclear.

Another example: The Severn Barrage. The BBC tells us "It is estimated it could provide about 5% of the UK's energy needs by 2020." `http://news.bbc.co.uk/1/hi/wales/5170792.stm`

Welsh Secretary Peter Hain commended the barrage with the same figure: "A barrage across the Severn estuary could generate massive amounts of clean, green energy - up to 5% of the UK's energy needs."

The BBC doesn't always get this wrong. `http://news.bbc.co.uk/1/hi/sci/tech/5168236.stm` They said electricity this time.

Figure 12.6. A *conparison* scale inside a Canadian refrigerator. Underneath the energy consumption (699 kWh per year) is a scale comparing this fridge with 'Modèles similaires'. The scale ranges from 'Uses least energy (699 kWh)' to 'Uses most energy (709 kWh)'. 'This model' is correctly marked by the black triangle at the extreme left of this scale.

The conparison

This is the most blatant deception of all. A conparison is not a comparison, but it's intended to look like one to a casual observer. And like all the best con jobs, it doesn't actually involve lying. Figure 12.6 explains.

Another example of conparison is the car advertisement that says a car is efficient 'for its class'. Invariably such a comparison indicates that the car is actually atrociously inefficient compared with all cars, so a special fictional 'class' of cars had to be created around it, usually 'the class of gas-guzzlers'.

Challenges – ensuring information is available at the point of consumption

There are challenges for market-based solutions to energy use.

It seems, for example, that many car drivers misperceive the cost of their journeys: they act as if the cost is just the cost of the petrol – thus discounting the road tax, insurance, maintenance, and depreciation of the vehicle. Road tax and insurance are fixed costs, paid up front. But maintenance and depreciation costs both increase with distance driven. The focus on the cost of filling the tank also neglects other more subtle costs: the costs of driving risks, for example – driving always carries risks of collision, congestion, aggravation, delay, or injury; the choice not to drive avoids all these risks, and of course replaces them with other costs or risks. The risk of actually dying or killing someone else, per unit time spent in the vehicle, may not be very high – it's similar to the risk of dying in a plane – but it would be nice if drivers were more aware of all the risks they are taking. Could we imagine a metered insurance system in which drivers have to pay a per-minute charge to cover the risks of participating in congestion, of being involved in an accident, or having a breakdown; this smart insurance meter could clock up charges all the time that a vehicle is on the road, rather like a taxi meter. The meter would be in wireless contact with a road-pricing system, and if a driver did participate in congestion, this fact could have an impact on their future insurance rates. (Stephen Salter has a brilliant way of implementing such a system without the central road-pricing system.) I think a financial display showing a live, perpetually increasing figure could do a lot to modify drivers' behaviours.

Furthermore, many cars do not make their drivers aware of the instantaneous cost of their driving. Boy racers who habitually roar from 0 to 60 between turns in a winding road may not realise that the gas'n'brakes style of driving costs significantly more than steadier brakes-free driving. Would it be a good idea to mandate some sort of live 'driving-economy indicator' in new cars? Simple 'miles per gallon' displays are quite common now, and presumably allow attentive drivers to spot some problems with their vehicles. Perhaps a stronger influence on driving behaviour could be achieved by a more complex driving-style monitor that spots gas'n'brakes behaviour too.

Notes

'Green' is not enough

Stretching of Language:

A hybrid bus uses 34% less fuel than a traditional bus, and it's described as a 'green bus'. ('London gets green buses' 2 November 2006)

A hydrogen fuel-cell bus is called a 'zero-emission' bus, even though its full life-cycle emissions of greenhouse gases are 40% or 140% *worse* than those of a standard diesel bus.

See hydrogen chapter.

Rockets and other examples of the redefinition of the English language

Richard Branson says http://www.virginearth.com/ "The technological feat of SpaceShipOne resulted in the Virgin Group licensing that technology to build five space ships and two White Knight carrier crafts and has given birth to a commercially viable space tourism industry for the future. Using the latest technology in hybrid rocket motors and next generation turbo fan engines SS2 and WK2 will be environmentally benign."

White Knight is powered by two General Electric J85-GE-5 afterburning turbojets. The aircraft was developed out of the Proteus design.

White Knight fuel capacity 2900 kg.

SpaceShipOne HTPB solid fuel and N2O. 2400 kg of propellant. 46.5 MJ/kg. (?)

Total energy for one SpaceShipOne flight (3 seats), duration 30 minutes, including three and a half minutes of weightlessness: 68 000 kWh total; 23 000 kWh per seat.

Compare with a round-trip long-distance flight on a 747: 10 000 kWh per passenger.

Flying into space once in a lifetime as tourist on SpaceShipOne: 1 kWh/d.

Redefining the word zero

"Make London green capital of world says Ken." [yvod5c] has some clueless suggestions in its list of ways to 'make London the greenest city on earth' –

Neighbourhood power stations to prevent energy waste during transfer from the National Grid.

Use of solar and wind power, and possibly wave power from the Thames.

[2dwnrl]

Today's plan calls for London's annual carbon dioxide emissions to shrink from 44m tonnes last year to 18m tonnes by 2025 - an average reduction of 4% each year.

Meanwhile, flight (outside St. Ken's control) – The expected increase in flights into Heathrow and City airports will see London's aviation emissions rise from 22m tonnes of carbon dioxide last year to 35m tonnes in 2025.

Ah, here is the article I wanted.

page 3 of thelondonpaper.com, Tue 27/2/07.

ZERO-CARBON BECKTON COMMUNITY UNVEILED

Welcome to Ken's ultra-green London

[2j2y4c]

the three-acre Gallions Park site will be home to 200 new flats.

The flats will “incorporate the best of modern construction and energy technology to ensure the development produces virtually zero carbon emissions”. Each high-rise housing block will incorporate solar panels and wind turbines on the roof and a combined heat and power plant which will be fuelled by wood chip waste from routine tree surgery across the capital, cutting energy use by up to 40 per cent.

Any excess energy created will be ploughed back into the National Grid and neighbourhood power stations will be used to cut waste during transfer. The flats at Royal Docks, Beckton, will have a large central greenhouse and allotments to encourage residents to grow organic vegetables.

Communal recycling and composting will be expected. Rainwater collected from the roof will be recycled to use for flushing toilets and in washing machines. The flats will be built from recycled aggregate reclaimed from debris left at old building sites, while all timber used will be from sustainable sources. A car-sharing club will be introduced and extensive cycling facilities will be brought in. Extensive children’s playgrounds are also planned.

Mayor Ken Livingstone announced the “One Gallions” consortium of construction company builders Crest Nicholson, BioRegional Quintain and Southern Housing Group will build the project.

A London Development Agency (LDA) spokesman said: “This is about urging developers to consider using green technology when building homes. If they can make a profit and make buildings greener, it may become the norm.”

Crest Nicholson has not yet finalised the flats’ cost, but half will be used for social housing while the rest will be sold on the commercial market. Work on the development is set to start next month.

[It’ll burn wood collected from around the city.]

THE GREEN DREAM

London’s 8000 bus fleet would be converted to diesel-electric hybrid vehicles.

Big Mac....

A Big Mac with a green coffee?

by Widiane Moussa. Monday, 8 January 2007

The world’s biggest burger chain begins serving rainforest-friendly coffee this week.

McDonald’s will source all coffee sold at UK outlets from farms that meet environmental and welfare standards.

With customers buying more than 143,000 cups of coffee a day, the company claims it is taking environmentalism “mainstream”.

McDonald’s has come under fire for its corporate ethics in recent years.

Steve Easterbrook, chief executive of McDonald’s UK, said: “This means that we can offer our customers great-tasting coffee that doesn’t cost the earth.”

Theories

A theory for why the BBC and others promote the useless 'turn off your mobile phone charger' advice:

(by Anton Ulrich)

Governments like to give advice that is guaranteed not to offend industry. Telling people to unplug their chargers is safe. Telling people to switch to fluorescent bulbs? Will offend manufacturers of old-style bulbs. Telling people to drive less? Will offend oil companies. Telling people to support renewable energy sources? Will offend the energy companies.

Local pressure

Local campaigns often oppose the installation of power facilities, even renewable ones. But in Sheffield, local campaigners are fighting to *keep* the 75-metre-high Tinsley Cooling Towers.

Data obfuscation

Is this another identifiable pattern?

Biting the finger, instead of looking where it's pointing.

Alf presents some data as evidence of view A. Bob says 'Alf has used the wrong data', citing a distinguished source expressing concerns about the data.

Notice Bob does not replace the wrong data with the correct data. This is perhaps a hint that Alf was right all along.

Example: the Thames barrier kafuffle in myths.tex.

Notes

83 Only 2% of Powergen's electricity is from renewables. [3x7538] states "Currently our electricity is generated from: Coal: 61%, Gas: 37% and Renewables 2%'. This renewable fraction is increasing steadily. But is it right to call a portfolio that is 98% fossil fuels "sustainable"?

86 The magic playing-field
Page 19 of 'The role nuclear power in a low carbon economy'. "The UK's renewable resources are some of the best in the world, and could provide all the UK's electricity over the longer term." Same page: "It is clear that nuclear power could generate large quantities of electricity, contribute materially to stabilising CO_2 emissions and add to the diversity of the UK's energy supply. However, even if we were to double our existing

nuclear capacity, this would bring an 8% cut on total carbon emissions from 1990 levels by 2035, and would contribute little before 2020. Nuclear cannot tackle climate change alone."
In Porritt's summary document, he again emphasizes this weakness of nuclear in "Advice to Ministers" – section 3. Point 3.4.

87 A SECOND EXAMPLE IS PROVIDED BY THE GUARDIAN... John Vidal, environment editor, Wednesday July 4, 2007, *The Guardian*, 'Nuclear expansion is a pipe dream, says report' [3c4bok]
... SUMMARISING A REPORT FROM THE *Oxford Research Group*. Barnaby and Kemp [2007]
Here is a quote from the report's own summary page: 'It is probable that by 2075 the world population will reach about 10 billion people. Assuming that countries generate one kilowatt of electricity per capita (probably an underestimation), and that they generate a third of their electricity by nuclear power (twice today's world share) to mitigate CO_2 emissions, the world would need to generate 3 TW of electricity by nuclear power-reactors, or 3000 reactors (assuming average capacity of 1 GW) - that's over four new builds a month from now on, compared to 3.4 per year which is the highest historic rate (France, 1977 to 1993).'
The original authors committed the magic-playing-field crime by encouraging the reader to compare 'four new builds a month' (the whole-planet figure) with '3.4 per year' (the France-only figure).
The reporter compounded the crime by (a) slavishly copying out whatever the boffins said, (b) failing to blow the whistle on this bogus comparison, and (c) cutting all mention of 'France' from the quote, so that there is no chance of the reader's detecting the bogosity.

Cheapening

How to make something sound cheap: express it as an 'equivalent price per gallon of motor fuel', because (even in America) the price paid at the pump is much bigger than the price of the raw material.

Remember

Make analogy of 'low-carbon' and 'low-tar'. The industry has deliberately promoted 'low-tar' cigarettes knowing that they would offer false reassurance without health benefits www.ash.org.uk.

13

Numbers for the planet

Britain's stuffed, what about the world as a whole?

Redoing the calculations for Europe

Can Europe live on renewables?

According to `TRANS-CSP_Full_Report_Final.pdf`, The European renewable energy potential is about 40 000 PJ/y – that is, 60 kWh/d per person. Their figure 2-12 breaks down into roughly 1/4 geothermal, 1/5 CSP, 1/5 Solar thermal 1/8 biomass, 1/15 PV, 1/8 wind, 1/15 hydro.

Once you take the argument from UK self-sufficiency to the EU level, aren't things much more favourable? Lower population density and more hydro, solar etc.?

Yes, there's more hydro (in Scandanavia and Central Europe) and more solar (in Southern countries), and the population density is a little lower than the UK. But most of Europe has less wind, wave, and tide.

Calculation to follow.

Wind: the heart of continental europe has lower typical windspeeds than the British Isles – in much of Italy, for example, windspeeds are below 4 m/s. Let's guess than one fifth of Europe has big enough windspeeds for economical windfarms, having a power density of $2\,\mathrm{W/m^2}$, and then assume that we fill 10% of those regions with windfarms. The area of the European Union is roughly $9\,000\,\mathrm{m^2}$ per person. So wind gives

$$0.2 \times 10\% \times 9000\,\mathrm{m^2} \times 2\,\mathrm{W/m^2} = 360\,\mathrm{W} \text{ per person}$$

which is **9 kWh/d per person**.

Hydro: hydroelectric production in europe totals 590 TWh/y, or 67 GW; shared between 500 million, that's 3.2 kWh/d per person. This production is dominated by Norway, France, Sweden, Italy, Austria, and Switzerland. I understand that there's little scope for further expansion of hydro in Europe. Let's imagine a 50% increase, giving **5 kWh/d per person**.

Wave: Taking the whole atlantic coastline (about 4000 km) and multiplying by an assumed average production rate of 10 kW/m, we get **2 kWh/d per person**.

Tide: tripling the estimated total resource around the British Isles (14 kWh/d per person) to allow for French, Irish and Norwegian tidal resources, then sharing between a population of 500 million, we get **5 kWh/d per person**.

Solar PV and thermal panels: most places are sunnier than the UK, so panels would deliver more power in continental europe. 12 m^2 of roof-mounted photovoltaic panels would deliver about **8 kWh/d** in all places south of the UK. Similarly, 12 m^2 of water-heating panels could deliver 20 kWh/d of low-grade thermal heat.

Total so far: 9+5+2+5+8 = 29 kWh/d per person. The only resources not mentioned so far are geothermal, and large-scale solar farming (with either mirrors, panels, or biomass).

Assuming an average raw power of sunshine of 90 W/m^2, and that 30% of the land can be used for biomass, with 1% efficient plants – not obviously feasible! – the power arriving in the form of carbohydrate would be 60 kWh/d per person. If (with a miracle of bioengineering) this power could be processed into useful form with an efficiency of 66%, we'd end up with **40 kWh/d/p**.

Alternatively, use the same area (2700 m^2 per person) for solar PV farming, with a power density of 5 W/m^2, and we'd get **320 kWh/d/p**. Solar PV farming would, therefore, add up to something substantial, if its cost could be got down.

Total Europe energy consumption in 2002: 1 082 mtoe. (Of which 306 industry, 338 transport, 438 other.)

Electricity: 1690 TWh/y (55% of total electricity) (and 928 PJ of heat) provided by classic thermal power stations. Nuclear 32%. Hydro 10%.

Redoing the calculations for the whole world

Do everything except solar first.

Hydro

"The IHA and the IEA estimate the world's total technical feasible hydro potential at 14 000 TWh/year (6.4 kWh/d per person), of which about 8000 TWh/year (3.6 kWh/d per person) is currently considered economically feasible for development. Most of the potential for development is in Africa, Asia and Latin America." http://www.ieahydro.org/faq.htm

Wind

It is estimated that 3% of the energy from the Sun that hits the earth is converted into wind energy.

Greenpeace and European Wind Energy Association say: Total available resources worldwide are estimated at 53 000 TWh. That's 24 kWh/d per person. That's onshore technically recoverable resource.

Some people think this figure is comforting: "It is clear that the world's wind resources are unlikely ever to be a limiting factor in the utilisation of wind power for electricity production." But I'd ask, "is 24 kWh/d per person enough for what people *want*?"

Wind. 2 W/m^2 flat ground at $v = 6$ m/s. Unfortunately most of the world's land has smaller wind speeds. Exceptional spots: central states of the USA (Kansas, Oklahoma); Saskatchewan, Canada; Southern extremeties of Argentina and Chile; Northeast Autralia; Northeast and Northwest China; Northwest Sudan; Southwest South Africa; Somalia; Iran and Afghanistan. Offshore: everywhere offshore north of 30°or south of 30°is good. America offshore study: winds above 7.5 m/s and depth $<$ 21 m: area on whole East Coast is about 5000 km^2 near Cape Cod and 15000 km^2 down as far as North Carolina. At 3 MW/km^2, that would offer 60 GW. Eastern US continental shelf estimated wind power: 400 GW. They cite a NREL report (on page 4) giving 95 GW estimate for using 1/3 of the area of $<$ 30 m waters. They then estimate an additional 386 GW in deeper waters. They examine a 1.5 TWh/y (170 MW) proposal by Cape Wind Associates (130 '3.6 MW' machines in 62 km^2 of Nantucket Sound.) (2.8 MW/km^2)

Tide

The average dissipated power due to tides is equal to 4 TW (Munk 1997, Egbert & Ray 2000). Kowalik [2004] He estimates that of this, 40–80 GW is tappable.

Wind again

USA wind document:

Wind energy, which produces virtually no CO_2 emissions, has been long recognized as an abundant potential source of electric power. A detailed analysis by the Department of Energy's Pacific Northwest Laboratory in 1991 estimated the energy potential of the U.S. wind resource at 10.8 trillion kilowatt-hours (kWh) annually, or more than three times total current U.S. electricity consumption.

Elliott et al. [1991] `http://www.awea.org/policy/ccwp.html`

Class 5 means power density is 400 W/m^2 at 30 m above ground; average windspeed 7 m/s. About 0.6% of land area is in class 5. (Mainly in North Dakota, Wyoming and Montana.)

Taking in class 3 as well (power density 300-400 W/m^2 at 50 m), wind speed 6.4 m/s (5.1–5.6 m/s at 10 m), the area is 13% of the contiguous USA. Could generate over 100 quads (fossil fuel equivalent) of electricity.

[570 TWh(e), 65 GW]. (I think this means raw fuel thermal energy.) With land-use restrictions, down to 47 quads.

The area for the land-use restrictions scenario is 435 thousand square kilometres.

Note they are assuming the delivered power is 1–2 W/m^2 in regions of class 3–6.

They converted from kWh into primary energy equivalent using 10235 btu per kWh.

total electricity consumed in 1990 was 2705 billion kWh.

ANSWER: USA, annual: 16 735 TWh if no land exclusion; 4628 TWh if maximum land exclusion.

That's 1911 GW or 528 GW respectively.

Or 42 kWh/d per person (300 million people).

(153 kWh/d per person if no land exclusion).

American capacity factor: 1468 MW of capacity generated 2.42 TWh/y. That's 19%.

Wave

Global coastal wave power resource estimated to be 3000 GW.

Highest wave energies are observed in the North Pacific, eastern Atlantic and southern coastlines of Australia, New Zealand, South America and Africa. Annual averages exceed 10 kW/m in nearly all areas.

For an estimate of the world coastline, use the data I used to find how many people live near sealevel. The world area within 100 km of the coast is 27.6 million km^2 (20%). So the effective length of coastline is 276 000 km.

Multiply by 10 MW/km, get 2,760 GW.

OK, so wave energy is 3000 GW, which is 0.5 kW per person, or 12 kWh/d each if perfectly harvested.

Assuming 10% harvesting, and 50%-efficient conversion to electricity, that's 0.5 kWh/d per person.

Geothermal

We already estimated the world sustainable geothermal resource on p. **??**. It's at most 10 kWh per day per person of electricity, assuming a population density of 43 people per square km (the world population density), assuming perfect heat pumps, and assuming that drilling is free; plus an equal amount of thermal power as a by-product.

In 1995, the exploitation of geothermal power was estimated to amount to on average about 4 GW total, worldwide. Which is 0.01 kWh/d per person.

People sometimes talk of Iceland supplying Europe's energy. The renewable reserves of Iceland (hydro and geothermal together) are estimated to be 50 000 GWh/y. That's just 5.7 GW.

Solar

Solar PV

- refer to solar.tex for projections of solar PV cost. The BP solar document says 3 TW(peak) of solar PV would reduce carbon emissions by 1 Gt C. This is said to be a plausible amount of PV in 2040.

Biomass. Arable land: 13%; permanent crops: 5%; sum = 18%. Total land area is 150 million km^2. All arable and crop land: 27 million km^2. (4500 m^2 each if shared between 6 billion.) Take over all this land, and produce power at 0.5 W/m^2 flat ground or 0.5 MW/km^2: 13.5 TW. (Ignoring the energy input required.) 54 kWh/d each.

Sheffield	28%
Edinburgh	30%
Manchester	31%
Cork	32%
London	34%
Cologne	35%
Copenhagen	38%
Munich	38%
Paris	39%
Berlin	42%
Wellington, NZ	43%
Seattle	46%
Toronto	46%
Detroit, MI	54%
Winnipeg	55%
Beijing 2403	55%
Sydney 2446	56%
Pula, Croatia	57%
Nice, France	58%
Boston, MA	58%
Bangkok, Thailand	60%
Chicago	60%
New York	61%
Lisbon, Portugal	61%
Kingston, Jamaica	62%
San Antonio	62%
Seville, Spain	66%
Nairobi, Kenya	68%
Johannesburg, SA	71%
Tel Aviv	74%
Los Angeles	77%
Upington, SA	91%
Yuma, AZ	93%
Sahara Desert	98%

Table 13.1. World sunniness figures. [3doaeg]

14

Whacky

whacky supply-side ideas - not science fiction - includes floating windmill.

Floating windmills? (notes)

Figure 14.1. Diagram of Hydro's proposed 'Hywind' floating wind turbine for use in 200 m-deep water. The hub height is 80 m above the water, the rotor diameter is 90 m, the floating substructure is 120 m deep, and the whole device weighs 8000 tons. Like a boat, the bit in the water is mainly hollow, but has a huge ballast-weight at the bottom to keep the windmill upright when the wind blows.
Image provided by `www.hydro.com`.

[`2jqwlm`] The wind turbine is mounted to a 120 m high floating concrete substructure. (So required water depth is greater than 150 m.)

Hub height 80 m. Rotor diameter 90(–120) m.

Mass 8149 t.

Incidentally, can you guess one reason why Hydro want to make floating windmills? "The company is ... considering the possibility of locating the wind turbine near an oil installation with the aim of supplying it with renewable energy." Yes, it's all to help us get fossil fuels more easily!

Could single-hull ships provide another platform? These decommissioned oil tankers have deadweights (i.e., cargo-carrying capacities) of 10 000 to 200 000 tons. The number of such ships is in the hundreds. The length of a 50 000 ton vessel might be 200 meters. The longest vessels of all are about 450 m long and 60 m wide. So I'd reckon that just one large (100 m diameter) windmill could be mounted per vessel. At 5 MW each, 1000 ships would carry a capacity of 5 GW.

Whacky little ideas

What about using the ordinary water system as a way of delivering useful heat energy to houses, from a central source such as a power station? This could reduce my local water-heating bill, and would be a cunning form of 'combined heat and power'.

My domestic water consumption is about 60 litres per day. The maximum power that could be delivered to my house by sending me warm (40 C) water instead of cold (10 C) is

$$CV\Delta T = 4200\,\text{J/litre/C} \times 60\,\text{litre/d} \times 30\,\text{C} \simeq 8\,\text{MJ/d} \simeq 2\,\text{kWh/d}.$$

Whacky phone

How about making a phone covered with solar cells, that way you can just leave it on a window sill to charge it when it is sunny. That is my 2 cents to save energy.

Well, a mobile phone doesn't actually use very much energy, so the *savings* from this innovation won't add up to much. But it's an interesting idea, isn't it – a phone that is its own solar charger. Does it add up?

Let's say the area of the mobile phone facing the sun is $40\,\text{cm}^2$. Let's assume 20% efficient solar panels, and that the phone is carefully tipped up to the right angle to face the sun, and that the sun is shining at full strength. Then the power from panels is 0.8 W. I think this is just enough to charge a phone. On a sunny day.

Whacky wind

Windmills on ships: Could a 1-MW turbine be mounted on a big ship? Ships could steer themselves to places in the oceans with good wind forecasts.

I'm assuming something useful could be done with the energy – some on-board chemical process.

Sails for boats

Is sailing a viable propulsion method for the sort of shipping society wants today?

Whacky ideas in the planetary engineering department

Climate change reduction with paint

Paint roofs white or silver (currently black) – so as to reduce solar absorbtion. If everyone created and maintained $100\,\text{m}^2$ of snow-white ground or roof, where once was a dark absorber, could this reflective surface conceivably avert global warming? A trustworthy answer to this question is certainly beyond me, but we can at least estimate whether a lick of paint is in the same league as a lifetime of fossil-fuel burning. A doubling in CO_2 is estimated to increase the 'forcing' by about $4\,\text{W/m}^2$. An increase of $4\,\text{W/m}^2$ is roughly equivalent to a 2% increase in the intensity of the incoming sunlight. So to 'offset' a doubling in CO_2 (from the point of view of its warming effect), we need to reflect 2% of the currently-absorbed sunlight into space. As a ball-park figure, this scale of reflection requires 2% of the earth's surface to be turned into reflector, which works out to $1700\,\text{m}^2$ per person.

This answer can be expressed in an exchange rate: the area that must be turned reflective per ton of CO_2. A doubling of CO_2 concentration will be achieved by burning very roughly 1200 GtC, that is, emitting 4400 $GtCO_2$. So the new reflecting area required per tonne is

$$2.3\,\mathrm{m}^2 \text{ per ton;}$$

for example, if you use 10 t per year, this neutralization strategy requires you to erect 23 m^2 of mirrors per year.

Ocean

Adding nutrients to areas of the ocean that lack phytoplankton is one way of reversing the effects of global warming explored by a new BBC TV documentary, Five Ways To Save The World.

Experiment: Half a tonne of iron was added to the sea. As a result, plankton bloomed and the ocean turned green.

By the end of the experiment, the scientists had calculated that the small area of newly fertilised phytoplankton had absorbed an additional 7,000 tonnes of CO2, the equivalent of 2,000 fully grown trees.

Plan for places that have iron: urea.

A computer-generated image of a 'cloudseeder' The futuristic fleet of yachts pumping sea-water into the clouds

A computer-generated image of a sulpher rocket Why launching sulphur rockets may stop global warming

A computer-generated image of a glass flyer, part of the global sunshade The deflective global sunshade designed to protect our planet

A computer-generated image of phytoplankton Could feeding the ocean's phytoplankton help save the planet?

A computer-generated image of an artificial tree The machines that mimic our natural carbon capturers

Multiplying the ocean's CO_2 guzzlers Adding nutrients to areas of the ocean that lack phytoplankton is one way of reversing the effects of global warming explored by a new BBC TV documentary, Five Ways To Save The World.

A computer-generated image of plankton Five Ways To Save The World Monday 19 February 2007 2100 GMT on BBC Two

Programme preview

Our oceans are teeming with phytoplankton: millions of microscopic plants beneath the waves that are vital to the marine ecosystem because they form the base of the marine food chain.

`http://news.bbc.co.uk/1/hi/programmes/6369401.stm`

Quotes from the net

For as long as humans have been on the Earth they have taken shelter from the Sun.

But with global warming now a major concern, imagine if you could do this for the whole planet.

One man believes it can be done - British born astronomer Roger Angel.

He thinks that by putting a giant sunshade – consisting of 16 trillion glass discs – in space, he can limit some of the Sun's energy reaching Earth.

Mr Angel has calculated that we would need to block only 2% of the Sun's rays to reduce global warming and cool the Earth.

But it would require a sunshade an incredible 100,000km wide.

This would be positioned 1.5 million km from our planet, orbiting at a location known as L1, a point of gravitational balance between the Sun and the Earth.

Getting a 20-million tonne sunshade into space, however, is not easy... or cheap.

As one of the world's foremost minds on glass optics, Roger Angel decided the best thing to do, instead of building one big shade, would be to construct many smaller optics that together make up the completed structure.

But a space shuttle can only carry payloads of up 25 tonnes to low-Earth orbit. To get the glass discs into space therefore requires a different approach.

An electromagnetic launcher could be located near the summit of a mountain where the air is thinnest and the resistance of the Earth's atmosphere less.

As a rocket rises past each electrical coil inside a 2km-long vertical tube, it gets an electric jolt making it accelerate faster.

The rockets would begin their journey deep inside the mountain and a massive electrical current - powered by the launcher's own hydro-electric power station - would propel the rockets skywards.

One rocket would fire off every few minutes.

After the rocket leaves the atmosphere, it must head towards the L1 point.

Within each rocket there is a stack of one million very thin glass flyers, and by triggering an electric charge, the top flyer is repelled away, and then the second and then the third; and so on.

Each glass flyer weighs only one gram - the same as a large butterfly.

On each would be a computer, a small camera to align itself accurately between the Sun and the Earth, and solar sails to guide it.

They would be receiving signals and doing two jobs: the first, to hold themselves perpendicular to the Sun so they cause the maximum shadowing, and second, not to move very fast so they do not hit their fellow flyers.

Each flyer ultimately has one function: to deflect sunlight a couple of degrees so it misses the Earth.

Roger Angel is convinced the sunshade will work in principle, but he estimates it will cost $4 trillion (£2 trillion) and take 30 years to complete.

Moreover, he hopes humankind will be wise enough to deal with the now widely accepted cause of global warming and cut CO2 emissions, so his sunshade will never be needed.

`http://news.bbc.co.uk/1/hi/programmes/6354759.stm`

Cloud-seeding yachts pumping 50 cubic metres per second worldwide.

Calculations show that if we can increase the reflectivity by about 3%, the cooling will balance the global warming caused by increased CO2 in the atmosphere (resulting from the burning of fossil fuels).

`http://news.bbc.co.uk/1/hi/programmes/6369971.stm`

sulphur particles similar to those erupting from volcanoes could act as a natural cooling device for the planet, by creating a "blanket" that would stop the Sun's rays from reaching the Earth. He envisages one million tonnes of sulphur to create his cooling blanket.

pull carbon dioxide out of the air by blowing it through a solution of sodium hydroxide. `http://news.bbc.co.uk/1/hi/programmes/6374967.stm`

could the CO2 collected be stored away forever?

Using existing oil drilling technology, channels thousands of metres deep would be bored into the sea bed.

A computer-generated image of channels drilled into the sea bed

The carbon dioxide gas would be injected into it, permeating the surrounding porous rock.

At this depth and low temperature, the carbon dioxide is denser than water, locking it in place.

"It cannot rise from there to the ocean floor," says Professor Lackner, "so it puts it away literally for millions of years."

It is going to take a great sea change in lifestyles to reduce carbon dioxide emissions to a manageable level.

The growing number of scientists and engineers proposing large-scale geo-engineering projects to combat these emissions say they are reluctant advocates.

BUT WHAT IS THE ENERGY COST OF MAKING THE SODIUM HYDROXIDE AND CONVERTING CARBONATE TO compressed CO_2?

`http://www.seas.columbia.edu/earth/lacknerCV.html`

Energy Volume 20, Issue 11 , 1995, Pages 1153-1170

doi:10.1016/0360-5442(95)00071-N

More notes from the internet

A simple sea creature could help to address the problem of global warming, a scientist claims.

Tiny tube-like salps mop up greenhouse gases by feasting on carbon-dioxide soaked algae from the oceans.

The US researcher told an American Geophysical Union meeting of his plans to adjust nutrient levels in the ocean to boost the sea animal's populations.

http://news.bbc.co.uk/1/hi/sci/tech/6217840.stm

The solid carbon pellet that emerges from the salp sinks and dissolves deep enough in the ocean to be effectively taken out of the carbon cycle.

Faecal pellets (Madin/WHOI) Salp pellets take carbon down into the deep ocean

Mr Kithil wants to increase the algae-eating salp population in the world's oceans by boosting its food supply.

He proposes to bring deep-water nutrients to the surface with arrays of wave-activated pumps.

With an infusion of nutrients, the algae bloom would mushroom, according to the untested proposal, and absorb mass quantities of dissolved CO2, before being eaten and excreted by salps.

The speculative idea includes releasing thousands of coiled pumps that un-spool when they hit water, extending like organ pipes.

Each pump consists of a flexible tube, up to 1,000m in length, which would draw cold, nutrient-rich water to the ocean surface.

Mr Kithil estimates 1,340 pump arrays, each consisting of 100,000 tethered pumps over 100,000 sq km, could sequester nearly a third of manmade CO2 annually.

Roll-on roll-off cargo-carrier with solar power, wave power, and sail power?

Scandanavian company Wallenius Wilhelmsen (WWL)'s "ES Orcelle concept vessel" http://www.netcomposites.com/news.asp?2837 has solar panels built into sails, and wave power collectors; and "could carry approximately 10,000 cars - around 50 per cent more than today's car carriers." Just in case the stubby little sails aren't sufficient to drive this huge load, the ship would also have our favourite 'renewable', hydrogen fuel cells, on board.

"Nature powers car carrier of the future"!

Does this hodgepodge sound completely implausible? How about a vote of confidence from the idea's promoters? "The company has no immediate plans to build a prototype of the E/S Orcelle."

(E/S stands for Environmentally sound Ship.) http://www.worldcargonews.com/htm/n20050405.548544.htm

"Nature powers ship of the future" http://www.2wglobal.com/www/newsFeatures/newsShowPages/show_wwwnews.jsp?newsRepository=wwwnews&oid=14900 http://www.2wglobal.com/www/newsFeatures/newsShowPages/show_wwwnews.jsp?newsRepository=wwwnews&oid=14906

15

Science fiction

Space solar

Advantage: always on. Power 8 times greater (no night, no clouds). Problem: impractical to launch. Power to payload ratio is at present a few 100 W per kg, which is too small Gibbs [2006].

Just think about it this way: it's proposed to zoosh a square-kilometre-sized solar panel into orbit using a rocket. That would be eight times better that just leaving the solar panel sitting on the ground in a desert. But the question is, how much would it cost to just make another seven solar panels and plop them in the desert too? How would that cost compare with the cost of the rocket? I find it hard to believe that the rocket is cheaper.

Figure 15.1. Putting things in space requires a bit of energy. Wernher von Braun alongside a Saturn booster. Mass: 3 000 tons. Capacity: puts 118 tons into low-earth-orbit.

Figure 15.2. Photo by NASA/Kim Shiflett

Other topics

Wind power from the jet stream. Kite power. Wind power on boats. Cold fusion. Solar in deserts. (Not science fiction.)

Ocean thermal power – see appendix.

Osmotic pressure – see appendix.

Flying wind farms

"Exploiting the jet stream represents the zenith (both literally and figuratively) of aerial wind-engineers' ambitions. Ken Caldeira, a climate scientist at the Carnegie Institution who has worked with Sky WindPower, estimates that harvesting just 1% of its energy would produce enough power for the whole of civilisation. But even at lower altitudes, the winds are stronger than they are at the surface, and that has attracted the attention of other inventors." `http://economist.com/science/tq/displaystory.cfm?story_id=8952080`

Kites reeling in and out; spinning helium balloons; and helicopters.

16

Ocean thermal

> "The tropical ocean represents a vast and yet untapped natural resource which can provide the globe with all of its required energy needs in perpetuity."
>
> (from `http://www.ocees.com/mainpages/otec.html`)

Ocean thermal energy

The idea is that in some places (to be precise, in tropical waters), the surface of the ocean is hotter than the bottom. This temperature difference can be exploited by a power station that lets heat go from the hot place to the cold place, diverting some of the heat into work along the way – just like a power station.

Such power stations are not an option in Britain, since we don't have warm surface waters, but for the benefit of readers in other countries with warmer water, or for British folks eager to invade tropical countries, let's estimate a theoretical upper bound on the power that could be obtained.

Let's assume the surface water is at a temperature of $T_{\text{hot}} = 20°\text{C}$, also known as $T_{\text{hot}} = 293\text{K}$ (that is, 293 degrees above absolute zero, which is $-273°\text{C}$). And assume the deep-ocean water is at $T_{\text{cold}} = 4°\text{C}$. What's crucial is the temperature difference $\Delta T = T_{\text{hot}} - T_{\text{cold}} = 16\,\text{K}$.

The maximum theoretical rate at which power can be extracted by a heat engine is proportional to the rate at which heat arrives on the hot side of the heat engine. In the sunny tropics, this rate of arrival of heat, per unit area, is $P_{\text{Heat}} = 250\,\text{W/m}^2$. (Here we're rashly neglecting loss of heat from the ocean surface by radiation.) The perfect heat engine can extract power at a rate

$$P_{\text{Ideal}} = P_{\text{Heat}} \frac{\Delta T}{T_{\text{hot}}} = 250\,\text{W/m}^2 \times \frac{16}{293} = 14\,\text{W/m}^2.$$

Realistically, I'd be surprised if anyone could make a heat engine with an efficiency better than 1/3, so our final answer for the maximum plausible production from an Ocean-thermal power station at the equator is

$$5\,\mathrm{W/m^2}.$$

[I should include unavoidable heat loss too.]

Perhaps this figure could be boosted a little by more careful farming of the hot water for the engine. If the incoming water were enclosed in thin pipes floating on the surface, its temperature could become greater than the 20 C assumed above, so the efficiency factor (16/293) could be boosted, perhaps to (80/293) or so. But such surface-floating inlet pipes sound unrealistically fragile for deep ocean deployment, and nobody has yet demonstrated such a system.

We can compare $5\,\mathrm{W/m^2}$ with the power outputs of the other renewable energy farms we've discussed.

Wind farm:	$v = 6\,\mathrm{m/s}$ (force 4)	$2\,\mathrm{W/m^2}$ flat ground
Solar		
Photovoltaic	20%	$16\,\mathrm{W/m^2}$ South-facing roof
	20%	$10\,\mathrm{W/m^2}$ flat ground
Biomass	1%	$0.5\,\mathrm{W/m^2}$ flat ground
Ocean thermal	$T_{\mathrm{hot}} = 20^{\circ}\mathrm{C}$	$5\,\mathrm{W/m^2}$ at equator
Nuclear fission		$1000\,\mathrm{W/m^2}$

I don't know how an ocean heat-engine would work – it would have to shift around huge quantities of water! An ideal one-gigawatt electrical power facility would have to pump about $300\,\mathrm{m^3}$ per second through heat-exchangers. Going by the figures from the experimental systems, the cost of pumping $1\,\mathrm{m^3}$ per second is about 200 kW, and so the cost of pumping $300\,\mathrm{m^3}$ per second would be about 60 MW. Allowing for non-ideal conversion (a factor of 3 or so), we're up to about 200 MW – so 20% of the power produced would have to go straight into running the pumps.

Fantasy time

Now imagine that we cover 10% of all tropical oceans with roaming heat-harvesting facilities. What's the total energy per person that we could gather, if it's shared out equally among 6 billion people? The tropical oceans are 40 degrees wide from North to South, and about 300 degrees wide. Each 10 degrees is 1000 km. So the total tropical ocean area is $120 \times 10^6\,\mathrm{km^2}$, or $20\,000\,\mathrm{m^2}$ per person. Using 10% of that area, and getting power at $5\,\mathrm{W/m^2}$, we end up with 10 kW per person, or 120 kWh per person per day – ignoring all energetic and economic costs associated with running the power stations and transporting the captured energy to its consumers.

So, in a future fantasy world, significant power could conceivably be extracted from oceans – but not enough for everyone to live at the current USA level of 300 kWh per person per day.

Simpler ideas: air-conditioning for people who live near the sea.

Combine this with the Uranium extraction plant?

NB, only works if deep water is nearby. A realistic assessment of potential world contribution, perhaps, is by taking the energy from a 2 km strip around tropical coasts.

Notes

Further reading: http://starbulletin.com/2006/06/03/news/story02.html http://www.nrel.gov/otec/ http://www.otecnews.org/ http://www.ocees.com/mainpages/otec.html http://www.worldenergy.org/wec-geis/publications/reports/ser/ocean/ocean.asp

17

Osmotic power

Osmotic power

Matthew Turner suggested this untapped power source to me.

I've never heard anyone else talk about it, but it is, on paper at least, roughly as big a potential power source as hydroelectricity.

Here's the idea. When river water mixes with salty sea-water, energy is thrown away. We end up with a mixture that can't be unmixed without a lot of energy being expended (at a desalination plant, for example). And whenever a physicist spies a mixture being made, he says, 'in principle that mixing could be modified and exploited to generate power'. To explain how this power would work is quite tricky, as it involves the phenomenon of osmotic pressure, which most university students find hard to comprehend. Perhaps we can start by describing a water-purification system called reverse osmosis.

Reverse osmosis is a way of making super-pure water for places like hospitals. Tubes are created from a special membrane, which allows water to pass through but not the impurities, and the impure water is passed through the tubes at high pressure. If the pressure is high enough, then a trickle of pure water will ooze through the membrane. To unmix the impure mixture we have to supply energy: we have to run the pump that pushes in the impure mixture.

In principle, reverse osmosis can be run in reverse. In which case, it's called osmosis(!). We put impure (say salty) solution inside the tubes as before (but don't pressurize it), and we supply purer water on the outside. The pure water has a natural urge to get mixed up with the salty solution, and tends to push its way across the membrane. This increases the pressure on the inside of the membrane. In principle, this increased pressure could be used to do work, for example to push salty water up a hill.

I really don't know whether this potential power source could ever be industrialized, but we can work out, according to the laws of physics, the maximum conceivable power. Incidentally, this would be a form of indirect solar power, as the osmotic energy was originally created by the heat of the sun causing water to evaporate from oceans.

We can find out the potential osmotic power of a region by estimating how much pure water reaches the sea, and multiplying by the osmotic energy per unit volume of sea water, which is about 0.8 kWh/m^3. This energy per unit volume is the same as the energy per unit volume of water falling through 280 m. So in principle, the osmotic power associated with every river meeting the sea is equivalent to a 280 m high hydroelectric dam with the same flow of water.

That sounds quite a lot! Perhaps countries with big rivers should look into this. How would it add up for the UK? As in chapter **??**, we chop Britain up into 'England' (represented by Bedford) and 'Scotland' (represented by Kinlochewe). The rainfall in Bedford is 584 mm per year, and in Kinlochewe it's 2278 mm per year. Don't forget that some of this rainfall ends up evaporating from the ground or out of plants. To allow for this water loss, let's ignore England's water altogether, and just count Scotland's. The area of Scotland, shared out among all Brits, is 1300 m^2 per person. So the osmotic power (per person) is

$$\begin{aligned} & \text{rainfall volume per day (per person)} \times \text{osmotic energy per unit volume} \\ = & \frac{2.3\,\text{m} \times 1300\,\text{m}^2}{365\,\text{d}} \times 0.8\,\text{kWh/m}^3 \\ = & 6\,\text{kWh/d}, \end{aligned}$$

if every river had a perfectly efficient osmotic power station at its mouth.

The rest of the world

Let's discuss big rivers. The Mississipi is the tenth biggest river in the world, discharging 16 200 m^3/s. Rather than persisting with the ideal osmotic energy density of 0.8 kWh/m^3, let's try to be realistic and assume that some yet-to-be-defined technology delivers one eighth of this: 0.1 kWh/m^3. Then the osmotic power from the Mississipi would be about 6 GW. The Saint Lawrence discharges 10 000 m^3/s of water, corresponding to a potential osmotic power of 3.6 GW. The Congo is four times the Saint Lawrence. The Amazon is twenty times the Saint Lawrence.

18

Technology

Decentralization

One strategy recommended by green campaigners to solve the energy crisis is to decentralize: generate power locally instead of in big central power stations.

"More local generation based around CHP and microgen will also reduce emissions."

But let's be clear. Decentralization is not really a way of getting off fossil fuels. It mainly means moving the fossil fuel burning from a big central facility to smaller local facilities.

A typical example of a micro-CHP system is the whispergen – `http://www.whispergen.com/main/products/`. This is a nicely-designed miniature power station *that burns fossil fuels*. This sort of decentralization *may* make better use of fossil fuel resources, but it has little to do with sustainability or renewables.

What is the potential saving from decentralization?

The main savings, we are told, would come from avoiding wasting heat at the power station itself, and from avoiding wasting energy elsewhere during conversion and transmission.

Let's be more explicit. We're imagining getting rid of all the big fossil-fuel power stations that dump their 'waste' heat into cooling towers and rivers, and replacing them by city-centre power stations that dump their heat into heating local buildings. Can they also use the waste heat to run *cooling* systems? How does that work?

Some questions: these local power stations still use fossil fuels. What do we do when the fossil fuels run out? And are the CO_2 emissions associated with all these local power stations still greater than the safe and fair emission levels? How does the local power station get rid of its waste heat in the summer months when the local buildings don't want much heating?

The total power delivered by fossil-fuel power stations is:

the total power they consume is:

the power dumped into cooling towers is approximately:

the power used for heating buildings is:

Diversity

Another 'solution' many debaters promote is 'diversity of supply'. "By having many sources of power, surely we will be OK." The problem is that this is like feeding five thousand people with five loaves and two fish. Just because you have diversity – loaves *and* fish – doesn't mean that you now have enough food. It takes a miracle to make 2 plus 2 add up to anything other than 4.

MicroCHP

See more from Fuellers document

Microgeneration, Decentralization

They keep on going on about microgeneration, but what contribution would it actually make? Does local production of electricity and heating from fossil fuels magically emit no CO_2? What are the numbers?

Answer is on page 14 of Sustainable Development Commission document. "As part of developing its Microgeneration Strategy, the DTI commissioned the Energy Saving Trust to look at the long-term potential of microgeneration technologies in the UK. Their report, published in 2005, covers all microgeneration technologies including micro CHP. It finds that by 2050, microgeneration could potentially provide 30-40% of the UK's total electricity needs and could help to reduce CO_2 emissions by up to 15%. In energy terms, microgeneration could supply just over 300 TWh of energy (14 kWh/d/p) by 2050, most of this from micro CHP and fuel cells."

Transmission

As we discuss different ways of obtaining energy, we tend to look increasingly far afield. The further away the energy comes from, the more we need to worry about the energy cost of moving the energy from A to B. If we had friends in the Democratic Republic of Congo who wanted to sell us energy, what would be the best way to get it from there to here, and how much energy would we lose along the way?

Energy is lost in two ways: inevitably, and accidentally. For example, when transporting gas along a pipeline, energy is inevitably lost through friction as the gas flows.

Complete accounting

Natural gas

Keep track of losses. For example, if someone uses liquid natural gas, probably the process of liquifying it used energy that won't be reclaimed. The re-expansion of the gas will make the pipes it expands through *cold*. Coldness is a useful resource in some places, but most likely it's not wanted and not used in the location where someone is burning the gas! This compression energy that's lost is said to be about 1/3 of the energy delivered in the fuel.

Liquefaction costs between 1996 and 2000 averaged $230 per ton, compared with $560 per ton between 1986 and 1990. The construction of an LNG plant costs $1-3 billion, a receiving terminal costs $0.5-1 billion, and LNG vessels cost $0.2-0.3 billion. Most of the world's LNG is imported by Japan, Korea, and Taiwan. Liquefaction is a very energy-intensive process, with typically about 8 to 9 percent of the plant's input used as plant fuel. LNG tankers. Each project requires several dedicated LNG tankers. These are among the most complex and expensive merchant ships ever built because of their double hulls and cryogenic lining. Each new 135 000 cubic meter (3 billion cubic foot) capacity tanker costs approximately $260 million. The tanker's LNG cargo is kept cool by evaporating a fraction of the cargo (boiloff) and burning it as boiler fuel. Typically, 0.15 to 0.25 percent of the cargo is consumed per day, during which the tanker will travel about 480 nautical miles. **Summary figure: 0.2% per 1000 km, plus 10% for liquefaction and regasification.** Regasification plant costs are typically considerably lower than liquefaction plant costs. Regasification energy requirements consume a further 1.5 percent of the delivered LNG.

LNG is liquid natural gas at almost atmospheric pressure (Maximum Transport Pressure set around 25 kPa) by cooling it to approximately $-163°$C. LNG is about one 600th of the volume of natural gas. Natural gas is typically 90% methane. 41 MJ per cubic metre.

During compression, pressures are up to 60 bar. (pure methane liquefies at $-161.6°$C). The density of LNG is roughly $0.4 - 0.5$ kg/l.

"Compressed natural gas" is gas at pressures up to 25 MPa.

Don't confuse LNG with LPG – liquid petroleum gas (propane).

NG losses. This page gives figures for leakage losses in the USA. About 2% of consumption.

Electricity

Electrical transmission uses high voltages (110 kV to 500 kV)

Underground is bad news because more power gets lost in resistive.

Long-distance transmission of electricity is almost always more expensive than the transportation of the fuels used to make that electricity. As a result, there is economic pressure to locate fuel-burning power plants near the population centers that they serve.

For a given amount of power transmitted, a higher voltage reduces the current and thus the resistive losses in the conductor. Long distance transmission is typically done with overhead lines at voltages of 110 to 765 kV.

Transmission and distribution losses in the USA were estimated at 7.2% in 1995, and in the UK at 7.4% in 1998. In the UK, the losses occur mainly in the local low-voltage network.

DC cables good for long distances: the loss in transport is only about **3% per 1,000 kilometres.**

Power lines in the UK are 400kV and 275kV

CO_2 emissions from power stations were 30% of the UK total CO_2 emissions in 2004.

Installed capacity of all power stations in the UK is 76,972 MW.

Transmission losses: 19% of losses are in high voltage system Distribution losses – 75% Theft or meter fraud or accounting discrepancies 6%

Losses of 31 000 GWh in 2004 5 700 lost in high voltage transmission (1.5% of original electricity); 23 000 GWh in distribution

I would guess from the map (p75) that typical distance gone from power stn to consumer is about 50 miles. So the power loss is 1.5% per 50 miles travelled.

Confirm this with the german CSP document. Loss per 1000 km for high voltage AC: 25%???

Wonderful document!

UK: Primary demand = 247.3 million tonnes of oil equivalent

Final energy consumption 2004: (by fuel) (**) 17% electricity, 33% natural gas, 47% petroleum other 3.5%

total: 173.5 million tonnes of oil equivlaent

by user: Industry: 19.5% Transport: 33% Domestic: 28% Others (eg services and agriculture) 12% Non-energy use: 7% (eg chemical feedstocks, lubricants)

Energy consumption by final user (2004) (from page 8 of trends document)

`http://www.dti.gov.uk/energy/inform/dukes/dukes2005/longterm05.pdf`

UK oil: page 10 of long term trends: [“Oil” includes natural gas liquids and process oils] UK still “produces” more oil than it imports, but probably not for much longer. (They are roughly equal). Why do we export an equal amount to what we import? ???

Production of oil is 100 million tonnes (p.a.?)

Gross electricity supplied: roughly 370 TWh in 2004; was 230 or so in 1970.

Superconducting cables

http://www.abdn.ac.uk/physics/case/et.htm

operated at 1000MVA

Has to transmit “large power” to be cost-effective. Although superconductors offer no resistance to direct current (dc), the fact that everyday power uses alternating current (ac), means that power loss is still incurred. This happens because an ac current generates radio waves that are absorbed by the insulating material in the cable. This happens whether the material is superconducting or not.

High voltage DC (HVDC) is used to transmit large amounts of power over long distances or for interconnections between asynchronous grids. When electrical energy is required to be transmitted over very long distances, it can be more economical to transmit using direct current instead of alternating current. For a long transmission line, the value of the smaller losses, and reduced construction cost of a DC line, can offset the additional cost of converter stations at each end of the line. Also, at high AC voltages significant amounts of energy are lost due to corona discharge, the capacitance between phases or, in the case of buried cables, between phases and the soil or water in which the cable is buried.

Superconductors: http://www.futureenergies.com/print.php?sid=237

require power to keep the cables cool.

How much?

RENEWABLES page 90. (2004) 3.81 million tonnes of oil equiv of which biofuels 83.8% – roughly half landfill gas and sewage gas; wood (domestic and industrial) 12.3%; cofiring 8.8%; waste combustion 12.1%; other biofuels 11.2% (eg short rotation coppice, farm waste). hydro 10.5% wind: 4.4% geothermal and active solar: 0.7% small scale hydro: 0.6%

Notes

(from Mott MacDonald 2001) Target loss levels for the national grid companies = 5.05 TWh/y.

Scottish power transmission losses are 2%. Scottish hydro-electric company losses 2.4%.

Main losses are resistive, apparently (from Mott MacDonald 2001 sec 4.5.2 and 4.5.8).

At higher voltages, corona loss increases.

Mvar is the name given to ‘reactive power’ rather than ‘active power’ (*i.e.*, in-phase power). Reactive power may be supplied by generators and they are paid for it.

Improve losses by changing to all Aluminium transmission lines, which are also lighter, and increased capacity for current. (Mainly the changes in conductors are made to increase capacity, not to reduce losses.)

Cables (in the ground) are usually copper, and lower resistance. But more expensive.

Langeled

Figure 18.1. Pipes for Langeled. From Bredero–Shaw http://brederoshaw.com/.

150 bar pressure, up to 70 million m^3 per day. 1200 km long. 44 inch diameter on the bit to the UK. Optimizing flow of gas, what's the optimal pressure?

Length of pipeline 1166 km. Power lost to friction in the pipeline?

Other options: liquify, put in tanker.

Remote power station, and Electricity.

Gas to liquid conversion first then transport liquid. (eg methanol)

Oil tanker

Actual cost of sending crude oil by tanker: about 0.1% per 1000 km.

Coal lorry

Road freight transport in the UK achieves 1 kWh/tkm. Coal is 26.7 GJ/tonne or 7 400 kWh/t. So energy lost per 1000 km is 14%.

Undersea electric cables

Stephen Salter says undersea DC cables are feasible over distances of hundreds of miles. A cable is being laid from the British mainland to Shetland and another from Norway to Holland. 800 kV is a good voltage for the longest distances. Are the losses the same as above-ground high-voltage DC?

AC electrical cables

High voltage losses are 15% per 1000 km for 380 kV lines and 8% per 1000 km for 750 kV. Each transformer station loses 0.25%.

DC electrical

HVDC: High Voltage Direct Current transmission. 600 kV or 800 kV. To transfer 50 GW, need a tract of land 100–150 m wide for pylons. (Lower than HVAC (800 kV).) DC cables good for long distances: the loss in transport is only about 3% per 1000 kilometres.

19

Hydrogen

> Hydrogen is just 'alternative energy' for those who don't understand the basic laws of thermodynamics.
> posted on `priuschat.com`

Hydrohype

Hydrogen seems to be presented as 'a solution' – phrases like 'the new hydrogen economy'. But let's get one thing straight. Hydrogen is an energy *carrier*, just as a rechargeable battery is an energy *carrier*. Hydrogen is not an energy *source*. To make hydrogen, you need energy, just as to make electricity, you need energy. You can make hydrogen in 'green' or 'brown' ways, just as you can make electricity in green ways and brown ways.

So, is hydrogen 'a solution'? It depends on what the problem is. If the problem is 'I want to power a bus with an energy carrier other than diesel', then hydrogen may be a solution; as might be rechargeable batteries too.

But if the problem is 'I want to have power without using fossil fuel', then 'hydrogen!' is not a solution, because 'hydrogen!' doesn't say where the power is coming from. Saying 'use hydrogen!' is just like saying 'use rechargeable batteries!' It avoids the real issue: where is the power to come from?

Production

`http://www.marketwire.com/mw/release_html_b1?release_id=229094`

This press release has useful facts on standard methods.

Alternate Energy Corp. Produces Hydrogen Without Greenhouse Gas (CO2) Emissions Company's Breakthrough Technology Is First to Economically Produce Carbon Free, Non Polluting Hydrogen Gas; Companies Installing AEC's Bulk Hydrogen Production Plants Will Be Qualified for "Green Credits" for Doing Their Part in the Reduction of Carbon Dioxide Emission

BURLINGTON, ON – (MARKET WIRE) – March 21, 2007 – Alternate Energy Corporation (OTCBB: ARGY), the developer of an innovative technology for the production of hydrogen and certain commodity chemical products, announced today that its breakthrough process technology will produce bulk quantities of pure hydrogen without any emission of greenhouse gases (carbon dioxide) into the environment. AEC's process produces valuable commodity chemicals while producing the hydrogen, but no toxic by-products – it is a totally "green" process.

AEC believes that its "green" technology for the production of hydrogen is the right technology at the right time. The primary methods of producing hydrogen gas today are "electrolysis" and "steam reformation of natural gas."

Electrolysis, used to produce about 5% of hydrogen today, is known to be highly energy-intensive. The cost of producing and delivering hydrogen from a central electrolysis plant is estimated at $7 to $9 per kilogram. One kilogram of hydrogen is equivalent to one gallon of gasoline. However, burning one gallon of gasoline will produce about 20 lbs. of carbon dioxide (CO2), but to produce that one kilogram of hydrogen by electrolysis will produce about 70 lbs. of CO2.

Steam reformation of natural gas, the method used today to produce about 95% of all hydrogen requirements, costs $4 to $5 per kilogram. However, this process produces carbon and if burned it would produce 11 lbs. of CO2.

Currently there is about $3 billion of hydrogen sold annually on a worldwide basis, a number that is expected to grow significantly as the new "hydrogen economy" takes hold.

Dr. Joseph Romm, Former Acting Assistant Secretary of Energy of the United States, in Testimony to the House Science Committee, stated, "A major technology breakthrough will be needed to deliver low-cost, zero-carbon hydrogen." He went on to say that "the burning of fossil fuels – oil, gas and coal – emits carbon dioxide (CO2) into the atmosphere where it builds up, blankets the earth and traps heat, accelerating global warming. We now have greater concentrations of CO2 in the atmosphere than at any time in the past 420,000 years, and probably anytime in the past 3 million years – leading to rising global temperatures, more extreme weather events (including floods and droughts), sea level rise, the spread of tropical diseases, and the destruction of crucial habitats, such as coral reefs."

Blaine Froats, CEO of AEC, commented, "We can produce hydrogen gas without any emission whatsoever. Not only is it cost efficient, but because the process produces a valuable commodity by-product a profit results. The process involves a chemical reaction that does not require the input of outside energy. When the reaction is finished everything used is spent and therefore there is no waste to be disposed of."

Mr. Froats added, "As discussed in our last news release, we are moving forward in a determined way to contract our first bulk hydrogen production plant, and will announce the commitment as soon as finalized. We remain confident that our process technology will have a strong impact on certain market sectors that will readily move to our environmentally friendly process, and gain 'green credits' for the benefit of us all."

About Alternate Energy Corporation (AEC; www.cleanwatts.com)

Alternate Energy Corporation (AEC) is energizing the hydrogen economy with its on-demand hydrogen production technology that provides bulk production of hydrogen and saleable commodity chemical products. These systems have global opportunities in multiple market segments. AEC's proprietary discovery in metallurgy and process technology permits the generation of hydrogen through a "green" process at a competitive level to the fossil fuel Kwh cost of energy. AEC believes its systems can have a revolutionary impact on the energy industry. For more information go to: www.cleanwatts.com

Forward-Looking Statements:

Statements herein express management's beliefs and expectations regarding future performance and are forward looking and involve risks and uncertainties, including, but not limited to, raising working capital and securing other financing; responding to competition and rapidly changing technology; and other risks. These risks are detailed in AEC's filings with the Securities and Exchange Commission, including Forms SB-2, 10-KSB, 10-QSB and 8-K. Actual results may differ materially from such forward-looking statements.

Fresh, distilled or sea water mixed with a combination of readily available, price-stable metals and chemical compounds are added together into a sealed container combined with a solution that allows for a chemical reaction to take place. Hydrogen gas (H2) is then produced (tested 99.9% pure), along with water and oxygen as non-toxic by-products. The process is completely bio-compatible (non-toxic and safe to the environment).

———

hydrogen-powered aeroplanes?

see flight.tex

(8) Gasoline has a density of 0.75 (water being 1.0) and liquid hydrogen has a density of 0.07. On the other hand, hydrogen provides three times the energy per pound of gasoline. The question is whether the lower weight makes up for the greater bulk. I was informed that it does, but I would like to have a reference that would permit me to replace this remark by something more definite.

In Socolow papers I think hydrogen is discussed; it doesn't offer a useful wedge, because to produce hydrogen from electricity (from extra windmills) and use in cars in place of fossil fuels, would require 4 million windmills, which is four times as many as the one-wedge figure, I think. This isn't a clear argument to me.

Hydrogen problems

Production: Hydrogen is three to four times as expensive to produce as gasoline (when produced from its most affordable source, natural gas).

Storage: Current hydrogen storage systems are inadequate for use in the wide range of vehicles that consumers demand.

Conversion: Currently, hydrogen fuel cells are up to ten times more expensive than internal combustion engines.

The 'zero-emission' bus is 3.67 m high, 12 m long, 2.55 m wide, 14.2 tonnes unloaded. Takes 30 seated and 21 standing. Range 120 miles, top speed 50 mph. Fuel cell gross power: 250 kW, net shaft power 190 kW.

Delivery: a truck can carry 3.3 tonnes of liquid hydrogen, equivalent to about 36 700 Nm^3.

Liquefying hydrogen costs 1/3 of the energy. 1 Nm^3, containing 3.54 kWh, requires more than 1 kWh.

Efficiency of on-site hydrogen supply: 35%–60%.

CUTE (Clean Urban Transport for Europe) was a project to demonstrate and test hydrogen technology for public transport. New buses operating in european cities carried 4 million passengers and covered more than 850 000 km. Overall efficiency measured in the CUTE project. "When analysing and interpreting the LCA (life-cycle analysis) results it is important to consider that the focus of the CUTE project was on the demonstration of the feasibility and reliability of the FC [Fuel Cell Bus] and H_2 technology, not on its efficiency." Indeed. When standard methods are used to make hydrogen (that is, make it from fossil fuels by steam reforming), overall primary energy consumption by the hydrogen buses was between 80% and 200% *greater* than that of the baseline diesel bus. Greenhouse-gas emissions were between 40% and 140% greater. If the hydrogen is made by electrolysis using renewable electricity (currently more expensive than the standard method), the overall greenhouse-gas emissions are 75% lower than those of the baseline diesel bus. The CUTE project summary anticipates that the hydrogen buses could be made more efficient.

Standard buses do 49 l diesel per 100 km. They expect the hydrogen buses to do 11 kg Hydrogen per 100 km.

Two alternative methods of manufacture: (electrolyser 5.8kWh electricity per Nm^3 hydrogen; steam reformer 7 kWh natural gas and 1 kWh electricity per Nm^3 hydrogen). The latter figures could be better: if a production plant is running optimally, (4.7 kWh natural gas and 1 kWh per Nm^3 hydrogen).

More references: http://www-formal.stanford.edu/jmc/progress/hydrogen.html

http://www.rmi.org/images/other/Energy/ hydrogen myths E03

Mark Peplow from Nature The hydrogen economy looks out of reach.

Like a drug addiction, need to get the junkies off it.

Norwegian doc: Hydrogen http://www.bellona.no/

BMW's 'Hydrogen 7' car: the boot is half taken up by the hydrogen tank. On hydrogen its range is 200 km. Tank holds 8 kg of liquid hydrogen at −253°C. It also has a 74 l petrol tank, and the engine can take either petrol or H_2. 12 cylinder engine. 260 hp.

"Hydrogen as a motor fuel is the answer to many environmental problems since there are no harmful emissions, no depleting of resources, no danger to the atmosphere, and it can be produced from a variety of renewable resources." `http://www.bmwworld.com/hydrogen/`

"unlike fossil fuels and traditional gasoline, hydrogen is available in virtually infinite supply."

Notes from the Fuellers

Appendix Three Storage Options and Production Techniques/Costs for Hydrogen

Hydrogen can be stored and this is the leading option - in very strong, very high pressure tanks (which tend to be rather heavy, and need to be of cylindrical or spherical dimension), typically above 600 bar. At 600 bar the energy density is 1/13th that of petrol, so together with the problem of tank geometry (which makes it hard to use vehicular space very efficiently), the vehicle is likely to have very limited range and/or luggage space.

Liquefied hydrogen can be stored in cryogenic tanks - essentially large thermos flasks - which need an ongoing supply of energy to totally reliable chillers to keep them super-chilled, otherwise the hydrogen must be dumped out of ports from the vehicle to avoid a pressure-explosion. This is the approach used on BMWs 2003 protoype. Very serious safety issues then arise if the vehicle is in a confined space such as a garage or enclosed (multi-storey) car park at the time.

Sodium boro-hydride can be used as a solid hydrogen storage medium tanks can be rectangular in form, so although the energy density achieved is about the same as the very high pressure tanks mentioned above in terms of tank contents, more hydrogen can in practice be stored in a given vehicle. There are substantial process losses (inefficiencies) in converting hydrogen to and from borohydride, and a significant process cooling requirement, but the explosion risk during a crash is far less. A safety hazard during a non-explosive-release type hydrogen fire (a fire not preceded by a pressure-explosion due to prompt conventional-high-pressure-tank breach or fracture) would be that hydrogens flames are completely invisible in air. This makes it difficult to tell if a leak is burning unless the flames are contacting other material, and so carries the added risk that it is easy to walk into a hydrogen fire inadvertently. Most hydrogen fires would be accompanied by explosive or very rapid hydrogen release from breached high price containment, with at the very least a very rapid conflagration that could not be overlooked. The risk is thus usually theoretical, but this risk could be more real with a leak from a (low pressure) borohydride tank that had found a source of ignition, as the leak would be slower and non-explosive.

Hydrogen could be mixed with methane to create vehicular hithane fuel (see above), which can be slightly more readily contained in the vehicle with resultant slightly better energy densities. Hydrogen could not, however, be mixed with propane (LPG). Being very energetic, the fast-moving hydrogen molecules would remain evenly mixed with the methane (also quite small energetic molecules) where it remains a gas (as methane does at most conceivable pressures, when not super-chilled) of their own accord, but this is not the case for hydrocarbon gases which may become partly or wholly pooled liquids under pressure - such as propane or butane.

Far more speculatively : new materials such as carbon nano fibres into which hydrogen can be absorbed under the combined influence of high pressure and low temperature, to be released as the pressure is dropped and the temperature increased. This has been talked about for 8 years now, but public, concrete non-nano-scale results have been notable by their absence.

We now explore the economic and other aspects of options for hydrogen production (and its existing uses and production) in a little more detail. Hydrogen should of course be produced in a manner that has very low carbon implications.

Large quantities of hydrogen are needed in the chemical and petroleum industries, notably in the Haber process for the production of ammonia, which by mass ranks as the world's fifth most produced industrial compound. Hydrogen is used in the hydrogenation of fats and oils (found in items such as margarine), and in the production of methanol. Hydrogen is used in hydrodealkylation, hydrodesulfurisation, and hydrocracking. It is used in the manufacture of hydrochloric acid, in welding processes, and in the reduction of metallic ores.

Some people argue that hydrogen could be piped in pure or hithane form to peoples homes and be used at 55% efficiency to generate electricity from home fuel cells (e.g. nuclear engineering international "NEI" - July 2005, page 16).

Most hydrogen today is produced by chemical reformation of hydrocarbons such as oil components (naphtha, heavy residues) and natural gas, although a small proportion is made by electrolysis where either the electricity is very cheap or there is a need for very pure hydrogen.

It is therefore important to note that most of the present industrial hydrogen production methods all release similar volumes of CO_2 to the atmosphere as that of the hydrogen produced. To eliminate CO_2 emissions from the present industrial production methods, carbon capture and sequestration (CCS) would need to be applied, adding to the production cost and reducing energy efficiency.

Closely related to the problem of storage is that of the infrastructure and handling technology at the motor vehicles fuel-filling station. Certainly at first impression, if distributed by road tanker, 13 times as many journeys would be needed; this may indicate that piped distribution could be justified above a certain scale (there are a number of cost figures for trucking, and for pipelines, on page 17 of NEI, July 2005, showing when this breakpoint is reached).

There are approximately 25 million cars and 3 million commercial vehicles in the UK using about 54 Mtoe of petrol or diesel each year, resulting in the emission of 150 million tons of CO_2 .

If the current UK road transport fleet were to be converted to run on hydrogen, it would need about 7.5 x $10^1 0$ cubic meters of hydrogen. Therefore, the UKs natural gas transportation system is of the same scale of that required for a fully integrated hydrogen economy in the UK.

If all the vehicles in the UK were to be replaced with hydrogen fuelled vehicles, existing UK hydrogen production would have to increase by about a factor of four.

If this hydrogen were to be produced by electrolysis, this would require about 50 GWe of dedicated UK generation over and above the 75 GWe of existing UK power stations.

Furthermore, this would need to be generating plant that does not emit CO_2 . Whilst renewables will undoubtedly contribute to this, at the present and forecasted rate of growth, it is unlikely that they will reach 10generating capacity by 2020, let alone the additional 60hydrogen economy is to be implemented by around 2050. Whilst these figures are broad estimates whose details can be debated, they serve to illustrate the magnitude of the "hydrogen economy" proposition and the severe challenges to realise it. The challenge of building an additional fifty 1 GWe zero CO_2 power stations, over those required for electricity production alone, is a major one. France has built sixty such stations in 30 years, but in the UK we probably do not have sufficient sites.

Worldwide : 360 bn gallons of petrol will be used in 2010 : this would equate to 260bn kg of hydrogen. To produce that much hydrogen across the world, global - electricity production would have to be increased by between 15% and 25% more than that needed merely to keep the lights on.

There are 440 nuclear stations operating worldwide, but providing enough electricity and hydrogen to meet the world's needs might need up to 3,500 nuclear stations.

The Fuellers note that the american government is so convinced that dual electricity and hydrogen production is the future that the US department of energy has now decided to construct a demonstration nuclear reactor to produce hydrogen in Idaho Falls.

The consortium that is producing the pebble-bed modular reactor (PBMR), very well suited to high temperature hydrogen production, aims to have the first prototype operating from 2012. Japans "JAARI" high temperature reactor reached 950 degrees in 2004 and is particularly aimed at hydrogen production. STAR, the small fast neutron reactor, is also aimed at this but lacks the backers and publicity that PBMR enjoys.

Hans Forsstrom, from the European commission, said the EU was also considering the use of high-temperature reactors to produce hydrogen. The process had a "big potential".

We refer again to NEI July 2005 : The maximum feasible net efficiency of low temperature electrolysis-based production of hydrogen is 75%. For a say light water reactor (PWR) operated not entirely at base-load, that achieves 32% real thermal efficiency, the net efficiency of hydrogen production by low temperature electrolysis is then 24% in comparison to the raw nuclear heat. If the high temperature (800 degrees+) steam-based electrolysis was used for the production, using nuclear heat in substitution for some (about 30%) of the electricity, the net heat-to-hydrogen efficiency would be 50%. This process has been tested at a small scale, and work is continuing at Idaho on scale-up.

Low temperature electrolysis-based production is in fact used for about 4% of current US production hydrogen produced this way costs more than using steam to reform hydrocarbons, but the hydrogen is particularly pure and therefore good for rocket fuel, research, and some other of the more demanding uses. The maximum unit size currently available (because there has not been demand for more) is 2 MWe each such unit produces 1000 kg per day of hydrogen at atmospheric pressure; the hydrogen then needs compression to say 20 or 30 bars before piping.

The problem is that hydrogen of lower quality, suitable for most processes, produced (together with CO_2) from hydrocarbons costs $1 to $1.50 per kg, whereas low temperature electrolysis-based production gives hydrogen at a cost of $4 to $6 per kG. The cost of high temperature (800 degrees+) steam-based electrolysis should lie in the range $2 to $4 per kg still too high.

The Japan Atomic Energy Research Institute is testing the Sulphur-Iodine Cycle process at its JAARI high temperature reactor, and claims a bulk production cost of $1.50 to $2 / kg-hydrogen should be possible, directly competitive with feedstock reformation techniques but without the CO_2. This is much talked-about at present; we very much hope that it proves to be achievable.

In terms of the economics and feasibility of hydrogen production from methane with CCS : Natural gas reformers can make hydrogen from natural gas at filling stations or in central plants. But whatever the price, electricity produced directly from natural gas will, arising from the physics, always be much cheaper than electricity made from natural gasderived hydrogen. A modern combined-cycle power plant is 50 per cent more efficient than a fuel cell vehicle, has access to cheaper wholesale natural gas prices, and does not need to cover the cost of hydrogen production, storage, and distribution. A modern combined-cycle power plant is thus the most energy-efficient way of using limited gas supplies. Central hydrogen generation plus distribution in liquid tankers has similar costs at the pump as hydrogen production at filling stations, and the same logic holds in both cases.

Electricity made from hydrogen produced by electrolysis cannot be cheaper than the original electricity; that would be the economic equivalent of a perpetual motion machine. This is worth bearing in mind if one contemplates using the output of costly renewables plant to make hydrogen, alongside the limited physical total scope for renewables in the UK.

Latest ways of making hydrogen

Hydrogen from aluminium and water

'New process generates hydrogen from aluminum alloy to run engines, fuel cells'

http://www.physorg.com/news98556080.html http://hydrogen.ecn.purdue.edu/

$$2\mathrm{Al} + 3\mathrm{H_2O} \rightarrow 3\mathrm{H_2} + \mathrm{Al_2O_3}$$

So by mass, 6 g of H_2 requires 54 g of Al and 54 g of water. With an 80-20 Al-Ga alloy, there will also be 17 g of gallium in there. That is, 125 g of on-board stuff per 6 g of hydrogen. However, if most of the water is recovered when the hydrogen is burned, the mass of water carried can be reduced. Assuming 50% water recovery, the hydrogen density would be about 6%.

Energy density of lead-acid batteries: 30–51 Wh/kg. Of the hydrogen delivered by Al-Ga-H_2O: 2200 Wh/kg. Volume density: 18 kWh/l.

Output: 9 kWh (of Hydrogen) and 9 kWh of heat per kg of aluminium (and how much water?) – using a gallium reaction-enhancer; a litre of water produces hydrogen with energy content of 0.4 l of petrol, according to the Grauniad.

Making Aluminium: 13 kWh per kg in the best modern plants (figures from Alcoa).

input: solid alloy of 20% gallium, 80% aluminium.

What's nice about this is the mass to be carried around is similar to petrol, and the so is the volume required.

Unfortunately, the Guardian presented this technology with the headline "For power just add water", thus perpetuating the awful 'water-powered car' rumour.

[2mst45]

Hydrogen from sugars

"Perhaps we should call it the pie in the sky economy.......In fact I have devised a way to power the world from floating pies (blackcurrent works best)...there are a couple of problems though...The pies take a lot of energy to produce, are difficult to transport and have a relatively short shelf life......Not to worry there a re economies of scal to be had and we can bake them using energy from renewable sources.......”Hmmmmm tasty” ” Dave, Darlington UK

20

Boat

Figure 20.1.

Shipping

To build an ocean liner would require an energy input of approximately 1.2 PetaJoules using current shipbuilding technologies. In other words, the embodied energy content of the liner would be 1.2 PJ.

Go here to get a comparison of transportation costs. `http://www.nrel.gov/lci/database/default.asp`

Drag

The drag of a boat produced by waves is

$$F = \frac{1}{2} c_{\text{wave}} \rho A v^2,$$

where A is the total wetted area of the hull, and the drag coefficient c_{wave} depends on the length and speed of the boat, with $c_{\text{wave}} \simeq 10^{-3}$ being a typical value. See Faber [1995], p. 186.

Let's make a model of transportation of junk by boat. Big boat, perhaps half of the mass is cargo. The propellors work like humming bird or helicopter – seize water and accelerate it.

Oh, I am curious, let's do that air-propellor boat idea too. Can a boat go direct upwind using a propellor? Wind speed v, boat speed u.

The power generated by the windmill is $f \rho A(v + u)^3$, where f is the Betz factor(?). The force on the windmill is $f \rho A(v + u)^2$, where f_2 is another Betz factor(?). The rate of work against this force is $f_2 \rho A(v + u)^2 u$.

Return to regular boat: its propellor spits out water with speed w. The force generated is something like $f \rho_{\text{w}} A_{\text{prop}} w^2$ and power required is something like $\rho_{\text{w}} A_{\text{prop}} w^3$. The drag force on the boat is something like $\rho_{\text{w}} A_{\text{boat}} v^2$; other forces to worry about are the drag from creating a bow wave. How does that work? Could estimate how much energy is in the wake of a big boat; how does it scale?

Quick rough estimates: big ferry in the north sea: v=10m/s, wave height is 1m; wavelength is 30m; one wave or so; energy per unit time t is

$\rho g v t \lambda h^2/t = 1000\text{kg/m}^3 \times 10\text{m/s/s} \times 10\text{m/s} \times 30\text{m} \times 1\text{m}^2 = 3,000,000\text{kgm/s/s} \times$ m/s which is 3000 kW.

Compare this with the drag force above, which is... plausible draught is 15m for very well laden container boat? width = 20m? drag power $= \rho \times 15 \times 20\text{m}^2 \times v^3 = 1000 \times 300 \times 1000 = 300,000\text{kW}$.

Hmm, could be my estimates are bad, but I am getting traditional drag is bigger than wave drag.

That boat, of length 100m, would have total displacement of $15 \times 20 \times 100 = 30\,000$ tons.

The power cost per ton is 10kW. So if a ton is taken a distance of 5000miles = 8000km = 8e6m, which takes 8e5seconds = 222 hours (10 days), which is 2220 units (kWh). Assuming the cost is an electricity unit cost (8p) then the energy cost of shipping a ton of junk 5000 miles is 177 pounds.

[This estimate completely ignores efficiency of propellor and of engine driving propellor]

If you cause a ton of junk to be shipped that distance each year (on food/computer/white goods/manufacturing grounds, say) then that's 6kWh per day average.

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a large bulk carrier carrying grain uses one gallon of fuel for 1600 tonne-miles of transportation. http://www-formal.stanford.edu/jmc/progress/arithmetic.html

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Transportation costs: 274 Btu per river-ton-mile, and 2,000 Btu per highway-ton-mile.

21

Space

electricity from space?

I can't spare space for this idea. Surely it's better to cut the rocket and invest the savings in extra solar panels?

`http://www-formal.stanford.edu/jmc/progress/oneill1.html`

22

Blimps

Blimps or airships. zeppelin, dirigible.

A blimp uses an enormous helium-filled balloon, which is lighter than air, to counteract the weight of its little cabin. Is there any point in blimps for transporting people or freight from A to B? First, let's compare a blimp with a car, van, or truck. The choice is: either we move the cabin from A to B with a huge balloon strapped to the roof, or with wheels strapped to the base of the cabin. With the balloon strapped on the roof, we add to the air resistance. With wheels instead, we add rolling resistance. We must also ensure that roads are constructed and maintained from A to B. Let's assume the road is in place. What speed would you like to go at? At any speed bigger than (20 mph?), the energy consumption of a road vehicle is dominated by its air resistance. Under these circumstances, it is a crazy idea to massively increase the air resistance.

Only at very low speeds could a blimp conceivably be better than road transport.

What if there are no roads? For example, are blimps useful for transport across seas?

Fundamentals:

Diameter $d = 10\,\text{m}$. Assume drag coefficient of 0.03, like a plane. air resistance, which is the force required, which is the energy per distance, is $\frac{1}{2} c_{\rm d} \rho A_{\rm p} v^2 =$

More work here....

84km/h.

Don't need to use energy staying up.

inability to overfly large mountain ranges.

Hindenburg's top speed having been 135 km/h (84 mph), the current airship "Spirit of Dubai" (a Skyship 600) can achieve only 50-80 km/h (30-50 mph), and the Zeppelin NT up to 125 km/h (78 mph).

Actual cost of operating an AI 600 between new york and atlantic city.

Estimated 4.5 million dollars.

`[37ozsq]`

http://links.jstor.org/sici?sici=0003-049X(1928)67

20 truckloads of goods straight from a factory in Japan to a warehouse in California in a day and a half, bypassing crowded ports and clogged rail lines.

Airships for freight

Airships to replace short-haul planes

coat with polymer PV? check power required.

and size?

http://www.aerosml.com/aeroscraft.asp

http://www.aerosml.com/airships.asp

http://www.aerosml.com/aeros-40D_spec.asp

Airship Length / 46.6 m Max Flight Speed 51 mph / 82kmh Operating Altitude Range 0 - 2,133m Envelope Length / 45.6 m Envelope Max Diameter / 10.6 m Envelope Volume Max 2,833 m^3 Engines 2 Teledyne Continental 4-Cylinder motors, IO-240-B Max Power 93.2 kW ea. Fuel Reserve (basic model) 45.141 Litters (30min. maximum continuous power) Fuel Capacity 287 Litters (usable) Fuel Consumption 34kg/Hour (@75% Cruise for 2 engines) Empty Weight 1,895.5 Kg Useful Load 980,5 Kg Number of Seats 5, Including 1 Pilot

Area exposed to sun roughly $300\,m^2$.

$1000\,W/m^2$ sun assume 5% efficiency (lightweight PV) 15 kW in full sun. Or 60 kW if revolution in lightweight PV gives 20%.

But it uses 180kW.

Absolute Airship Speed Record Zeppelin NT Friedrichshafen, Germany 60.4 knots (111.8 km/h) 27 October 2004 http://www.stevefossett.com/html/main_pages/records.html

Alternative titles or subtitles:

Sustainable energy—without the bullshit

This isn't going to be easy.

– without the rubbish, claptrap, garbage, twaddle, hooey, bunkum, baloney, trash, balderdash

Numbers, not adjectives – sustainable energy without the claptrap

Multiplication and division
– Sustainable energy, without the poppycock

Phone-chargers, water-powered cars, and greenwash. A straight guide to Sustainable energy, without the white elephants

Chargers, Cars, Windmills, and Aeroplanes – A straight guide to Sustainable energy
(Make a humorous title by choosing a list of memorable famous contrasting eco-symbols.)

No exaggeration, please
– Sustainable Energy in Numbers.

Numbers, not adjectives
– A Quantitative Guide to the Sustainable Energy Problem.

Green Enough?

Addition and division
– Sustainable energy, without the poppycock

You figure it out – Sustainable energy on the back of an envelope

NUMBERS, NOT ADJECTIVES.

Your sustainable energy crisis

THE ENERGY BOOK

THE ENERGY QUESTION

The honest energy broker

Honest energy

Straight energy talk

Energy counts. Counting energy. Energy arithmetic.

Let's do the numbers – What everyone needs to know about sustainable energy

Huge? Sustainable energy, without the bullshit.

Huge? The sustainable energy crisis in numbers.

A back-of-the-envelope approach to the sustainable energy pickle

The sustainable energy crisis and arithmetic

No exaggeration, please
– An Honest Guide to the Sustainable Energy Problem.

Numbers not adjectives – a rough guide to the energy problem

Numbers not adjectives – sustainable energy without the claptrap

The Book of Numbers

Energy for dummies

Numbers not adjectives – a rough guide to our big energy problem

Sustainable energy, with the numbers

Sustainable energy, without the nonsense

Sustainable energy, without the conmen

Mega-delusion

The sustainable energy crisis and what you can do about it

The sustainable energy deficit

The sustainable energy conundrum

Order-of-magnitude morality

Every little helps? – Sustainable energy without the poppycock

Cause for terror

The sustainable energy puzzle

Energy Numeracy

Go Figure!

The sustainable energy jam

The sustainable energy enigma

Sustainable energy for the year 3007

Sustainable energy – humbug and arithmetic

Sustainable energy 101

Sustainable energy – mirages, humbug and arithmetic

Balancing the books

Balancing the equation

The sustainable energy pickle

The sustainability pickle

The sustainable energy problem

Cut the crap

The Rough Guide to Sustainable energy
Come clean on energy
Get real on energy
Realist's guide to energy
Not easy
Energy lessons for fossil-heads
Fossils are dead (like 'fur is dead')
Physics for fossils

AFTER FOSSILS
Beyond fossils
Repowering
Power plan
Power lines
Power trip
Power switch
Power facts
Honest power
power base
power broker
power play
staying power
straight zip vim power up front direct
oomph in numbers
power planning
power plans
cut the baloney
cut the twaddle
cut the garbage
cut the bull
cut the hooey
cut the gas
cut the trash
cut the whopper
cut the rot
cut the guff
cut the bosh
cut the bilge
cut the hogwash
cut the hot air
power plan
power cycle
true power
Let's get the facts right
Repower
What every fossil needs to know about energy
Energy lessons for petrol heads and tree-huggers
Brown to Green – what everyone needs to know about energy
E
Watt and how
Watt future
Watt next
Watt's next
Next Watt
Halving your cake and heating too

E by gum
THE ENERGY FILES
flogging two dead metaphors with one stone
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Power lines

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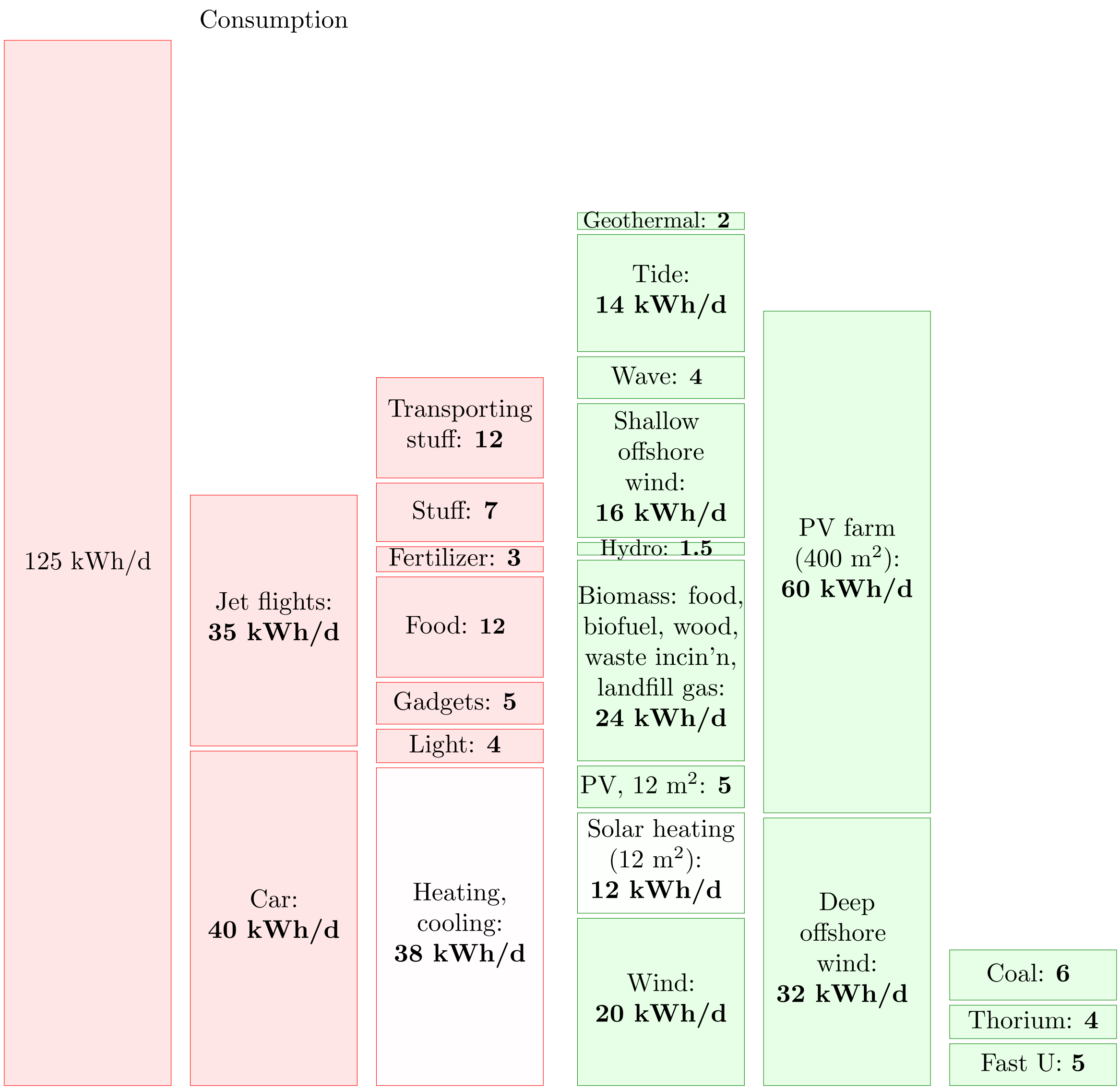
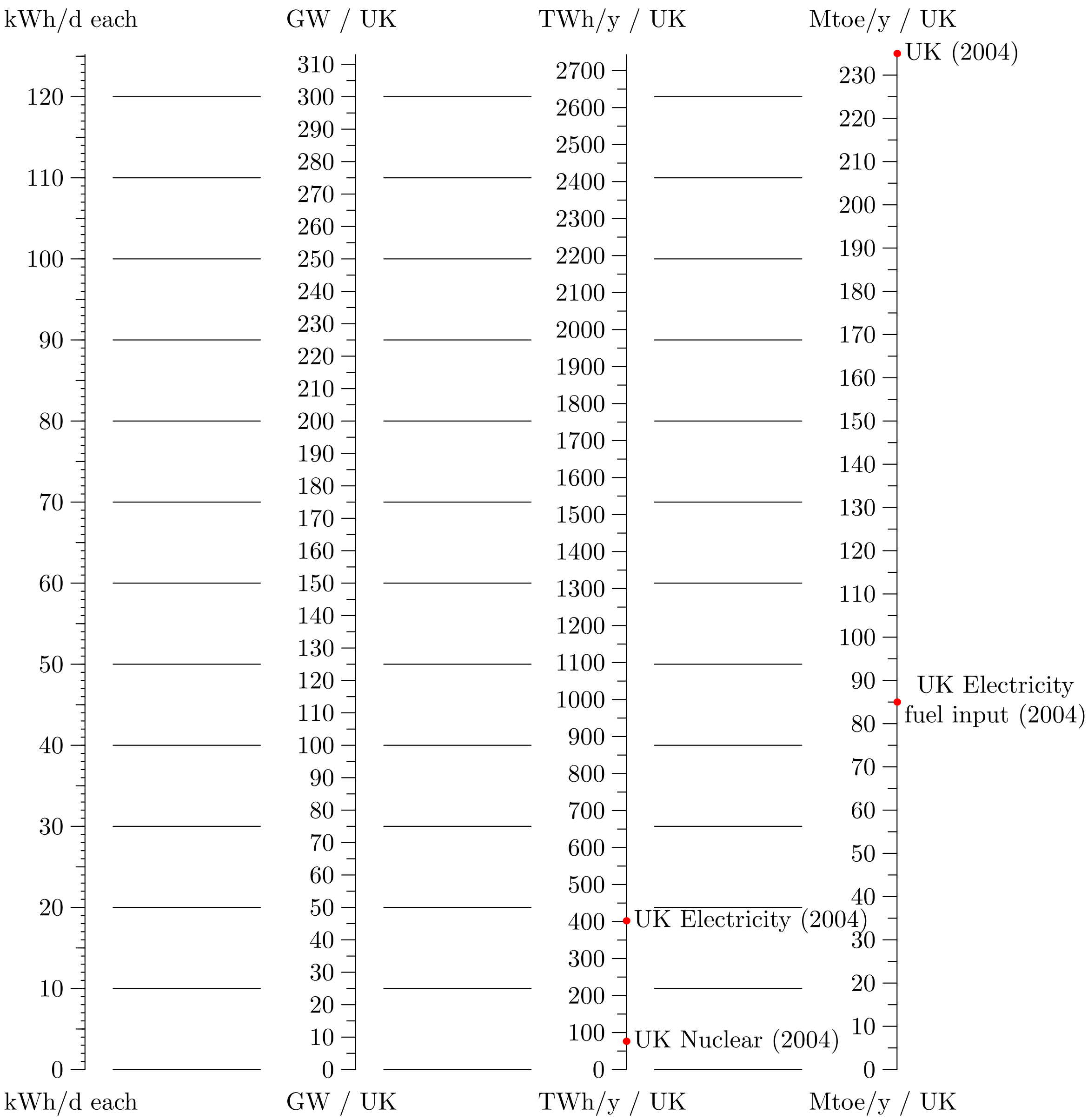
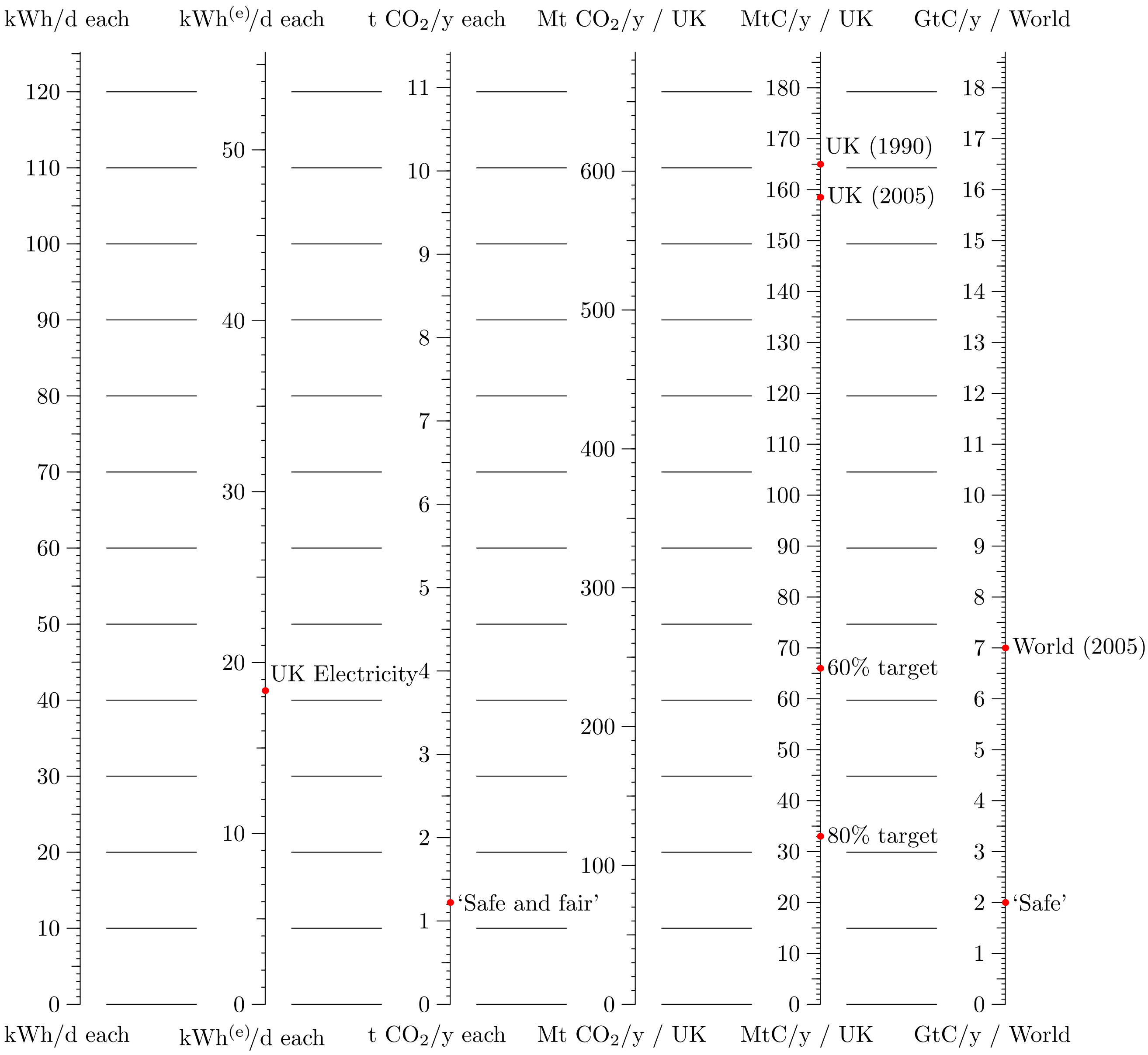

Consumption
125 kWh/d
Jet flights: 35 kWh/d
Car: 40 kWh/d
Transporting stuff: 12
Stuff: 7
Fertilizer: 3
Food: 12
Gadgets: 5
Light: 4
Heating, cooling: 38 kWh/d
Geothermal: 2
Tide: 14 kWh/d
Wave: 4
Shallow offshore wind: 16 kWh/d
Hydro: 1.5
Biomass: food, biofuel, wood, waste incin'n, landfill gas: 24 kWh/d
PV, 12 m²: 5
Solar heating (12 m²): 12 kWh/d
Wind: 20 kWh/d
PV farm (400 m²): 60 kWh/d
Deep offshore wind: 32 kWh/d
Coal: 6
Thorium: 4
Fast U: 5

Power translation chart



1 kWh/d	the same as 1/24 kW	'UK'	= 60 million people
GW	often used for '**capacity**' (peak output)		
TWh/y	often used for average output	USA:	300 kWh/d each
1 Mtoe	'one million tonnes of oil equivalent'	Europe:	120 kWh/d each

Carbon translation chart



kWh	*thermal* energy exchange rate: 1 kWh ↔ 250 g of CO_2 (oil, petrol) (for gas, 1 kWh ↔ 200 g)
kWh$^{(e)}$	*electrical* energy is more costly: 1 kWh$^{(e)}$ ↔ 445 g of CO_2 (gas) (Coal costs twice as much CO_2)
t CO_2	tonne of CO_2
Mt C	million tonnes of Carbon

'UK'	= 60 million people
'World'	= 6 billion people
UK:	160 Mt C per year (2005)
USA:	20 t CO_2/y each (1.5 GtC/y total)
World:	7 Gt C per year (2005)

To avoid 2 C global warming, need < 2 Gt C/y