The Numbers Game

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Often what distinguishes fact from opinion is a number, perhaps expressing how big something is or perhaps the relative size of two effects. What can determine whether something is important, relevant or even practically possible may be a number. Putting numbers to effects is an integral part of science, particularly physical science. One of the core elements of science is critical thinking. Numbers give the critical thinking that is central to science an edge over that in many other disciplines. Numbers aren't necessarily just things you look up in a reference book or on the web. With the background that most people have who are taking our meteorology course, you can work out how big many effects are, or at least get a good enough idea to support an argument you're putting forward or maybe to demolish someone else's argument.

This note shows how to estimate some numbers that are relevant to global warming. The working doesn't come from textbooks but is simply working that I did when I wanted to know how big the effects were. The idea is to use basic science concepts, along with some relevant data that can be looked up readily to produce the number of interest. All the examples involve making some plausible assumptions that simplify the issue but aren't likely to introduce a very big error. Often an answer that is within 20% of the ideally accurate figure is quite good enough. Sometimes there is no ideally accurate figure. Even if you don't feel inclined to follow all the working, look at the questions below, look at the answers, which I've given immediately after the questions, and you'll see some surprises.

This document has expanded enough to make it useful to include a summary of the questions. They are:

1) *If all known reserves of coal in the world are used up, how much extra CO_2 will end up in the atmosphere?*
2) *Will the same kind of sum for oil add a lot more CO_2 to the atmosphere?*
3) *The known increase in CO_2 in the atmosphere since industrialisation is 200 ppm. Is this figure consistent with the amount of coal and oil that has been brought up from the ground by mankind since industrialisation?*
4) *How long would coal power fuel mankind's overall use of power at the rate of 1.5×10^{13} W (about current consumption) if it were the only source of power?*
5) *How far does an average car go before it emits 1 tonne of CO_2?*
6) *How long will it take the Greenland ice-sheet to melt due to excess radiant energy from global warming?*
7) *If all the coal and oil reserves were converted into trees, how big an area would they cover?*
8) *If in future when oil runs out mankind has to produce in biofuels (mainly ethanol and biodiesel) a volume equal to the current world production of crude oil, estimate how much land will need to be devoted to biofuel crops if today's techniques are used.*
9) *If in the UK we have to derive all our energy use (including heating, transport, manufacturing production, etc.) from electricity, how much extra electrical generating capacity will be necessary?*
10) *If all the energy from a year's consumption of coal, oil and natural gas ends up heating the world's atmosphere, what temperature rise would that produce?*
11) *What mass of CO_2 would need to be sequestrated to reduce the atmospheric concentration by 1 ppm?*

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1) *If all known reserves of coal in the world are used up, how much extra CO_2 will end up in the atmosphere?*

Answer: 100 – 200 ppm (parts per million), depending on how much is absorbed by the oceans and biosphere

The idea: find the mass of the atmosphere and the mass of CO_2 produced by processes that burn coal and see how many ppm of the atmosphere is added by the CO_2.

a) What is the mass of the atmosphere? From the lecture course, the amount of air is equivalent to a layer 8 km deep surrounding the Earth all at ground level pressure and density. Take this density to be 1.2 kg m^{-3}. Take the radius of the Earth (from the Astronomy course) to be $R = 6375$ km. The volume of air is therefore the surface area of the Earth times 8000 in m^3 and the mass is the volume×density. These are all the facts needed.

Hence mass of atmosphere = $4\pi R^2 \times 8000 \times 1.2$ kg $\approx 5\times10^{18}$ kg

b) Coal reserves are currently quoted at about 500 gigatonnes, i.e. 5×10^{11} tonnes = 5×10^{14} kg. Coal is substantially carbon but also contains the elements oxygen, sulphur, hydrogen and some mineral content. When you burn coal you get sulphur dioxide, hydrogen, other products and of course a pile of ash and clinker. Let's say that 50% of the mass is converted into CO_2, i.e. 2.5×10^{14} kg of carbon.

One CO_2 molecule has a mass of 44 atomic mass units of which 32 are oxygen and 12 carbon. Hence for every 12 kg of C there will be 44 kg of CO_2, the extra mass coming from oxygen taken out of the atmosphere. Hence 2.5×10^{14} kg of carbon will produce $(2.5\times44/12)\times10^{14}$ kg of CO_2, i.e. 9.2×10^{14} kg of CO_2.

At the current rate of absorption, about a third of CO_2 produced ends up in the atmosphere, the remaining 2/3rd is absorbed by the biosphere and oceans. There is a limit as to how much these systems can absorb. Question 7 here looks at one aspect of this issue. Let's say that about half the produced CO_2 will be absorbed, leaving in the atmosphere about 4.6×10^{14} kg of CO_2. This represents about 100 ppm. If almost all of the CO_2 ends up in the atmosphere this still is 'only' some 200 ppm.

2) Will the same kind of sum for oil add a lot more CO_2 to the atmosphere?

Answer: not a lot, about 50 - 100 ppm.

The idea: as above, find the world's oil reserves and estimate how much CO_2 can in principle be produced by using them up. Compare this with the mass of the atmosphere.

Take world oil reserves to be 1.5×10^{12} barrels, slightly more than current figures. 1 barrel is about 150 litres and a litre is 10^{-3} m^3. Crude oil comes in varying densities; take 900 kg m^{-3} as representative. Hence by mass, oil reserves are about $(1.5\times10^{12} \times 150 \times 900/1000)$ = 2×10^{14} kg. Oil reserves by mass are less than coal reserves and in practice are being used up faster.

Oil is used to produce the world's plastics, many chemicals, tars etc. so not all of it ends up getting burnt. In addition, the molecules making up oil contain more hydrogen than is found in coal. It's probably not unreasonable to say that at most 50% of the mass of oil is carbon that in one way or another will end up as CO_2 through use of the oil in power stations, heating and as fuel for transport. Hence 1×10^{14} kg of carbon from oil will produce, by the same line of calculation as with coal, about 3.5×10^{14} kg of CO_2. This is equivalent to 50 – 100 ppm depending on how much is absorbed by the biosphere and oceans.

3) The known increase in CO_2 in the atmosphere since industrialisation is 200 ppm. Is this figure consistent with the amount of coal and oil that has been brought up from the ground by mankind since industrialisation?

Answer: yes, if one adds in an estimate for CO_2 from deforestation since industrialisation.

The idea: An accurate calculation would need to add up the known annual coal and oil production since industrialisation. We shall ignore wiggles in the annual production curves and make a sweeping statement that coal production has roughly doubled every 40 years and oil production doubled every 25 years to current levels. In fact both coal and oil production are flattening off from this continual increase and indeed many argue that 'peak oil' has just about been reached, after which world production will decline. Nonetheless, our assumption will produce a 'ball-park' figure for historic consumption. The conversions given above will enable tonnes mined to be converted to ppm of CO_2.

Our simple mathematical model is that the annual production of coal $P_c(t) = 8\times10^9\times2^{(t-2010)/40}$, where t is the date in years that has a value before 2010. 8×10^9 tonnes is the annual production in the year 2010. Likewise, the annual oil production is $P_o(t) = 4\times10^9\times2^{(t-2010)/25}$.

With these formulae for annual production, it is simple to estimate the total production up to the year 2010. For coal it is $8\times10^9\times40/\ln2 = 4.6\times10^{11}$ tonnes $= 4.6\times10^{14}$ kg. For oil it is $4\times10^9\times25/\ln2 = 1.44\times10^{11}$ tonnes $= 1.44\times10^{14}$ kg.

From the discussion above, about 50% of the mass of both coal and oil produces carbon that ends up as CO_2. Hence we expect the mass of CO_2 produced from all the coal and oil mined to be about $(6\times10^{14}/2)\times44/12 = 1.1\times10^{15}$ kg $\equiv$ 220 ppm of the atmosphere. This figure may seem in good agreement but at first sight it is surprisingly small. The current paradigm is that about one third of CO_2 production ends up in the oceans and one third ends up in organic matter. However, since historical times the organic inventory of the Earth is clearly less rich than it used to be, with deforestation being conspicuous. There has therefore been a net contribution to atmospheric CO_2 from the organic inventory of the Earth and not a net absorption. Question 7 looks at the carbon content of forests. From the figures there, if the forest coverage of the Earth has gone down from 50% (frankly, a guess) to today's value of 30% then this is equivalent to generating about 100 ppm of CO_2. That makes a total of 330 ppm generated by coal, oil and wood burning since industrialisation and if a third has been absorbed by the oceans, then that leaves an increase in the atmospheric CO_2 until 2010 of 220 ppm. So reality is close to expectation. I should add that this calculation has been done 'on-the-fly' and not rigged to give this answer.

The conclusion is that the observed increase in atmospheric CO_2 is consistent with mankind's known use of natural resources. The figures 'stack-up', which is encouraging confirmation that our numbers in this and related calculations are valid.

4) How long would coal power fuel mankind's overall use of power at the rate of 1.5×10^{13} W (about current consumption) if it were the only source of power?

Answer: about 25 years

The idea: look up how much energy is produced for each kg of coal and compare the total energy available from the world's coal resource to the amount of energy mankind uses in a year. This will give the number of years the coal will last for if it were the only energy source.

Burning coal produces about 6.7 kW h kg^{-1} of heat (~24 MJ kg^{-1}). For some high quality coal it's more but we're assuming average stuff. [In coal-fired power stations the heat is turned into electrical power with an efficiency of about 30%. Therefore the electrical power that could be generated from each kg of coal is about 2 kW h. This produces 1.8 kg of CO_2, from the previous calculation, i.e. about 0.9 kg CO_2 for every kW h of electricity. The figure for oil is slightly less but not much different.].

5×10^{14} kg of coal, the world resource quoted earlier, can generate 3.3×10^{15} kW h of heat. Using energy at the rate of 1.5×10^{13} W = 1.5×10^{10} kW, in 1 year (8766 h) mankind uses a total amount of energy of 1.3×10^{14} kW h. Hence the total lifetime of the coal reserves would be only about $(3.3\times10^{15}/1.3\times10^{14}) = 25$ years. This is a starkly short time.

In reality coal isn't the only source of power but at the moment fuels about 25% of mankind's needs. Its present rate of consumption is about 4 TW (4×10^{12} W) which over a year equates to $(4\times10^{12} \times 8.766) = 3.5\times10^{13}$ kW h and at this rate coal reserves will last $(3.3\times10^{15}/ 3.5\times10^{13}) \approx$ 100 years, just 4 times the figure above, as you'd expect. You'll often see figures of 150 to 250 years quoted but recently world reserve estimates have been downgraded and also coal consumption rates have risen steadily.

If you look up the figures, the present consumption rate of oil is about 5 TW and since there is less of it you can see why oil reserves at the present rate of use won't last your lifetime. This is rather scary.

5) How far does an average car go before it emits 1 tonne of CO_2?

Answer: about 4000 miles

The idea: find how many litres of petrol need to be used to produce one tonne of CO_2 and then use the fuel consumption rate of miles per litre to convert this into miles. This is the basic scientific method. As a cross check, you can do the simpler task of looking up the typical CO_2 production figure that's now quoted for all cars and see if the number agrees.

CO_2 has a molecular weight of 44 of which 12 is carbon. Hence 1 tonne of CO_2 contains 12/44 tonnes of carbon, i.e. 273 kg. Petrol is a mainly a mix of hydrocarbons, with octane C_8H_{18} being typical. C_8H_{18} has molecular weight of 114 of which 96 is carbon. [The chemists will baulk at such a complex mixture being represented by one molecular species but all we're looking for is a broad brush representation of the carbon to hydrogen ratio]. Hence 273 kg carbon comes from 273*114/96 = 324 kg of octane. This assumes that all the carbon in petrol is converted into CO_2.

The density of petrol is about 700 kg m^{-3} and hence 324 kg occupies 0.463 m^{3} or 463 litres. i.e. 1 tonne of CO_2 is produced by about 460 litres of petrol, which will cost you around £500 at today's pump prices in Britain. Most of the cost is tax. Taking an average fuel consumption of 8 miles per litre, the petrol will get the car 3700 miles down the road. Of course there is quite a bit of variation of this distance with different cars whose petrol consumption can be as much as twice this figure or less than half of it.

The quoted CO_2 emission figure for a 'typical' mid-range car is about 150 g km^{-1}. There are 10^6 g in one tonne. Hence this mid-range car will produce 1 tonne of CO_2 in travelling $10^6/150 = 6666$ km, or about 4150 miles. You'll get this figure from the calculation above with a fuel consumption of 9 miles per litre or with an adjustment of the carbon to hydrogen ratio that represents petrol.

6) *How long will it take the Greenland ice-sheet to melt due to excess radiant energy from global warming?*

Answer: thousands of years

The idea: estimate the extra rate of energy input and use the latent heat of ice to find the rate at which this will melt ice. Ignore the fact that the ice has to be heated from below freezing or that the melt water may be more than 0°C. These effects will slow the process.

This calculation is outlined in the lecture notes in the section of global warming with some additional comments. Take the extra energy incident on the ice and absorbed by it as 1 W m^{-2}. There are about 3×10^7 seconds in a year and hence in 1 year this extra energy input is 30 MJ m^{-2}. The latent heat of ice is about 330 KJ kg^{-1} and hence this heat can melt $30\times10^6/3.30\times10^3 \approx 90$ kg of ice in 1 year. Solid ice has a density of about 900 kg m^{-3} so the upper limit to the amount of ice that can be melted is 0.1 m^{-3} per square metre, i.e. 10 cm thickness. Much of the Greenland ice-sheet is over 1.5 km thick (indeed a lot is over 2 km thick) and hence at this rate of melting it will take over 10,000 years to melt it. What makes the time so long is the huge latent heat of melting of ice.

7) *If all the coal and oil reserves were converted into trees, how big an area would they cover?*

Answer: about 50% of the area of the inhabited continents

The idea: use a figure for the mass of trees in an average forest area to see how much forest is needed and hence what fraction of the available land on Earth that this represents.

This may sound a silly question but it is an interesting one. Of course the coal and oil is used by mankind and much of the carbon converted into CO_2, which ultimately is taken up again in the biosphere, largely by plant life and the oceans. There is a limit to how much the oceans will absorb, a limit that decreases the warmer the oceans get, so supposing the entire remaining coal and oil reserves ultimately generate new plant life, what's the maximum we can expect the Earth to accommodate? There's lots of grass and scrub on Earth. The maximum carbon uptake over a given area is surely with trees.

Forests come in all different sizes and densities. [There's an old joke along the lines of "How do you find your way out of an Icelandic forest when you're lost?" The answer is "stand up". That will change if Iceland warms significantly!]. We'll look up some data on the world's forests that should give a 'ball-park' figure.

The average amount of biomass in the world's forests is about 110 tonnes ha^{-1} which, since there are 100 ha per square km, converts to 1.1×10^4 tonnes km^{-2}. The world's forests cover 38×10^6 km^2, about 30% of the continents that have forests and 25% of the world's total landmass.

From earlier sums, coal reserves are about 5×10^{14} kg and oil reserves about 2×10^{14} kg. Coal came from plant life and oil from animal life. Let's suppose that that the fraction of carbon in wood isn't much different from that in the average of coal and oil so a total of 7×10^{14} kg of reserves gives rise to 7×10^{14} kg of trees. At the density of our forest above, then those trees will cover $(7\times10^{14}/1.1\times10^7) = 6.4\times10^7$ km^2. The Earth's total land mass covers about 150×10^6 km^2, and hence the total afforested area needed is $(6.4\times10^7/150\times10^6) \approx 0.42$ times the total land available on Earth, i.e. 42% of the Earth will be needed. If you exclude Antarctica, the land is about 130×10^6 km^2 and hence the % cover needed rises to 50%. Very interesting!

In summary, to sequester the carbon given off by using up the Earth's fossil fuel resources of coal and oil will require an **extra 50%** of the inhabited continents of the world to be covered with forest. At present, 30% of this land is forested so in short, it can't be done. Other forms of plant life cannot consume nearly the mass per hectare of trees and even if you think of life in the seas you aren't going to generate 100 tonnes per hectare of new life over vast areas of ocean.

Conclusion. The world's population have been deforesting the world over the past century so any plan for more forest area on a huge scale is going to be a tough one to implement. It's true that present tundra areas may in future support forests with continued global warming but surely a plan to increase the forested area of the world by half as much again as it now is will be absolutely an upper limit for what might (unlikely) be possible. That's an extra 15% of available land turned into forest. 50% is needed from the calculation above so that at least two-thirds of the carbon released cannot be taken up by plant life, and in reality an even larger fraction. This is true no matter how slowly the reserves are used up. Trees take half a century to grow a decent size and hence creating new forests takes time. Even at present emission levels, about 3 gigatonnes of CO_2 emissions is not taken into the biosphere annually but left in the atmosphere, which confirms the conclusion that trees and other plant life aren't going to save the planet from ending up with significantly more CO_2 in the atmosphere than it now has.

8) If in future when oil runs out mankind has to produce in biofuels (mainly ethanol and biodiesel) a volume equal to the current world production of crude oil, estimate how much land will need to be devoted to biofuel crops if today's techniques are used.

Answer: about 2×10^7 km^2, around 13% of the Earth's land surface.

The idea: look up yields of typical biofuel crops per hectare and the biofuel production from raw materials and compare with the world's crude oil production.

Biofuels have a lower energy content per litre than petrol and diesel as we now get them so the sustainable scenario above won't give mankind as much energy as is now available. Crude oil is used to produce other products than fuel for transport and heating, such as plastics, but in future biofuels will have to substitute for this too. When oil runs out, the world's population will be larger than it now is so asking for today's volume will give less per person than we now get. Biodiesel is produced mainly by oilseed rape, soybeans and palm-oil; bioethanol by wheat, maize and sugar-beet, for example. Take the production of crude oil from the major oil-producing nations as 85 million barrels per day, i.e. 1.3×10^{10} l $d^{-1} \equiv 5\times10^{12}$ l y^{-1}. This is the biofuel target.

The yield of biodiesel (energy content 35 MJ l^{-1}) from oilseed rape is typically 1300 l ha^{-1} (litres per hectare). Bioethanol (energy content 21 MJ l^{-1}) yields are higher, e.g. 2600 l ha^{-1} from wheat and 5400 l ha^{-1} from beet. Sugar-beet clearly does best but crops need rotating so all the land couldn't be converted to sugar-beet production. Since we're just making estimates, take biofuel production to yield 2500 l ha^{-1}.

The area of land needed in crops will therefore be about $5\times10^{12}/2500$ ha or 2×10^{9} ha. This figure excludes farm overheads, storage, production and distribution facilities. There are 100 ha per sq km so the area required is 2×10^{7} km^{2}. This is about 13% of the Earth's land surface (including Antarctica!).

Conclusion: Given the other calls on land surface and the fraction of the area that is suitable for crops, it will not be feasible in future to produce this quantity of biofuel. In a sustainable economy, alternative energy sources will need to be found for many of the uses that currently rely on products from crude oil. Some uses, like aviation fuel, will still need a similar product.

The connection of many of these calculations with meteorology is through global warming. The mitigation of global warming will come through the use of alternative energy to fossil fuels but as the numbers above show, simply replacing oil by biofuels and coal by wood isn't sustainable. Large changes have to be made in the way society 'does things', particularly energy consumptive activities such as transport, heating, building and many everyday practices. There will be big changes ahead. Watch this world.

9) If in the UK we have to derive all our energy use (including heating, transport, manufacturing production, etc.) from electricity, how much extra electrical generating capacity will be necessary?

Answer: some 4 times the generating capacity we now have.

This is quite a scary question, or at least the answer is quite scary. The necessary figures come from public statistics. The current average use of electricity per individual in the UK is about 800 W. The average energy use in the UK per individual (i.e. the total energy consumption rate divided by the UK population) is about 5 KW. Existing electrical capacity is about twice the average use, to cater for fluctuating demand, and perhaps in the future fluctuating demand can be dampened by suitable management and what we do may change but even so we will need at least 4 times the electrical generation capacity that we now have. Since most of our exiting electrical power comes from coal and gas stations, the future requirement for renewable power will not simply be to replace these stations when they are phased out but there will be a need to provide very much more electrical power than we now generate. No further comment!

10) If all the energy from a year's consumption of coal, oil and natural gas ends up heating the world's atmosphere, what temperature rise would that produce?

Answer: no more than 0.015°C

This isn't such a stupid question as it may seem. The greenhouse effect is said to be the cause of long term temperature rise but we are using more and more fossil fuels so is this also an unsung contributing factor? The point of singling out fossil fuels (I could have included nuclear too) is that renewable sources like wave, wind, tidal, solar and hydroelectric all heat the atmosphere whether we tap them for usable power or not. The fossil fuels (in 2015 generating about 80% of world power) create *extra* heat. Lots of coal is used to produce electricity but that electricity is used immediately to produce power in motors and electronics, and heat and light in buildings. The devices that use it don't destroy the energy but effectively convert it to heat that is dissipated in the surroundings. Heat within buildings all leaks out into the atmosphere. Likewise for oil and gas. The net result is that perhaps it takes several stages but the chemical energy in almost all fossil fuels gets converted into heat. This includes petroleum and diesel. The exception is the small fraction of raw material that is converted to chemical ingredients, plastics, bitumen and other 'permanent' materials.

First, how much atmosphere is there? From the first part of question 1, the mass of the atmosphere is about 5×10^{18} kg. The energy conversion of fuel into heat is mainly near the bottom of the atmosphere but convection and atmospheric motion will quite quickly spread the heat over the troposphere. The atmosphere above the troposphere, 20% in round figures, won't be involved in this, so the mass figure above is a slight overestimate. We'll take the specific heat capacity of air as 1 kJ kg^{-1} K^{-1}, meaning that it will take about 5×10^{18} kJ of energy to raise the temperature of the atmosphere by 1 K (or 1°C, which is the same increase).

Various web sites give values for world energy consumption but it's not clear what they measure. Do they include the 'waste heat' from power stations, for example, which may be easily as large as the electricity produced? I'll start with ball-park figures for annual fossil fuel production at 2015 rates. I'm using production here rather than consumption but stockpiles aren't changing much on the scale we're talking about. World coal production 8000 Mt per year; world oil production 27 billion barrels per year; natural gas production 3500 billion cubic metres - pity about the different units. I need to convert them all to Joules. Not all coal produces the same energy per kg and similarly for oil and gas, so again ball-park figures are needed. 1 tonne coal $\equiv 3\times10^{10}$ J; 1 barrel oil $\equiv 5.8\times10^{9}$ J; 1 m^3 natural gas $\equiv 3.8\times10^{7}$ J. With these conversions we get the energy in one year's production of fossil fuels is: coal 2.4×10^{17} kJ; oil 1.57×10^{17} kJ; gas 1.33×10^{17} kJ. They are all a similar size. The total is 5.3×10^{17} kJ per annum, equivalent to 1.69×10^{13} Js^{-1}.

Now combine the results of the previous two paragraphs and the fossil fuel energy budget when converted into heat might be expected to heat the atmosphere by $(5.3\times10^{17}/5\times10^{18})$ °C, or about 0.1°C per annum. This is an interesting statistic (I didn't know the answer beforehand). Even the most alarmist global warming doom monger would agree that the atmosphere isn't heating up at this rate. What's going on? The above calculation assumes that all the heat stays in the atmosphere. It doesn't. Some goes into the oceans, and it takes about 4 times more energy to make a given change of temperature to a kg of seawater than a kg of air; some goes into space. This raises another question, namely why does the atmosphere heat up at all since space is an infinite sink for heat?

The heat lost from the top of the troposphere (the tropopause) into space is determined by Stefan's radiation law. For a rise in temperature of ΔT, the tropopause can radiate an extra energy of $4\sigma T^3 A\ \Delta T$, where σ is Stefan's constant (5.67×10^{-8} W m^{-2} K^{-4}), T is the temperature there (say 215 K) and A the global surface area (5.1×10^{14} m^2). The question to ask, then, is what temperature rise is sufficient to radiate the extra energy produced by mankind's use of fossil fuels? Since the earlier estimate gave the extra energy as 1.69×10^{13} Js^{-1} (i.e. Watts), then the temperature rise ΔT is given by $(1.69\times10^{13}/(4*5.67\times10^{-8}*215^3 *5.1\times10^{14}) = 0.015$ degrees.

There we have it. Even ignoring the heating of the sea, the figures above suggest that mankind's use of fossil fuel at the rate being extracted in 2015 can't heat up the atmosphere by more than 0.015 °C. With that heating, the atmosphere can radiate into space the extra energy produced by the fossil fuels. There is no cumulative effect, year on year. The effect is much too small to account for global warming over the past century as being due to increased use of fossil fuels. The calculation is what physicists call a 'back of the envelope' estimate, ignoring finer points. Nonetheless it gives an idea of what the numbers are and shows that one has to be careful in global warming calculations to think through what is going on. To put the numbers in the context of the IPCC's emphasis on 'radiative forcing', 1.69×10^{13} W over a surface area of 5.1×10^{14} m^2 is 0.033 Wm^{-2}. Compare this with the radiative forcing of CO_2 which is about 1.5 Wm^{-2}, some 45 times greater.

11) *What mass of CO_2 would need to be sequestrated to reduce the atmospheric concentration by 1 ppm?*

    Answer: about 8 million megatonnes (8 gigatonnes)

The total mass of the atmosphere is, from the earlier estimate, about 5×10^{18} kg. Most of that is N_2 molecules of mass 28. CO_2 molecules have mass 44 and hence 1 ppm will have mass approximately $44*5\times10^{18}\times10^{-6}/28 = 7.86\times10^{12}$ kg.

Current carbon sequestration is apparently about 20 million tonnes a year, enough to change the atmospheric concentration by ¼ percent of 1 ppm. Using technology to 'suck CO_2 from the atmosphere' isn't a recipe for avoiding the effect of CO_2 on global warming, for there is just too much CO_2 to make the process feasible on the scale needed. It may help to ease the problem of building a new coal or oil-fired power station and so it is technology worth pursuing as one of many contributions to easing the use of coal, oil and natural gas. Planting millions of square km of forests would help but do we really want what are now landscape vistas to be a sea of trees everywhere, stretching to the horizon all round? You can get some idea of what that might be like by travelling through the Swedish countryside. Even on the top of hills you often don't see for miles because of all the nearby trees. The numerous lakes actually make Sweden an attractive place but it's not a model for world landscape. Maybe the oceans can be pressed into hosting a lot more life, like algae, but it is bizarre to be digging up coal and oil at a great rate and then complaining that the waste product of their use is changing the Earth for the worse for many people. The solution is clearly to leave the stuff in the ground and to 'decarbonise' the energy supply chain as much as possible, much more quickly than we have been doing. Investing more in renewables is a 'no-brainer'. Investing more in nuclear fusion research makes sense. Even disposing of nuclear waste from fission power stations becomes a small issue compared with disposing of gigatonnes of CO_2.

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