

Energy: Issues of Scale and Perspective

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In dealing with many issues, having a comprehension of the scale involved is critically important. Often this simply involves relating quantities to values one is familiar with. In other cases one must consider things in the appropriate time interval, system scale, or both. An area where the scale issue is particularly important, but often misunderstood, is that of energy use, carbon dioxide (CO₂) emissions, and climate change. In the following pages, these interrelated issues are discussed in more common terms, an approach which is essential when considering possible solutions and educating the public to permit its informed participation in developing energy policies.

A prevalent unit used when discussing global emissions is gigatons (Gt), current global annual anthropogenic CO₂ emissions being about 29 Gt. But, what is a gigaton? It is, of course, a billion tons; however, this answer conveys very little in terms of perspective. A much more practical answer is that a gigaton is a cubic kilometer of water (1 cubic meter of water = 1 metric ton). For those of us who still think in terms of miles, a cubic mile of water weighs a bit over 4 Gt. Thus if we were to dispose of all of our CO₂ emissions, in terms of mass we would have to “bury” the equivalent of 29 cubic kilometers, or about 7 cubic miles of water on a yearly basis (without accounting for the density difference between water and CO₂). If, for instance, CO₂ is injected deep underground at the required storage depths, the needed volumes will be somewhat larger because, at the prevailing storage temperatures and allowable pressures, the CO₂ is a supercritical fluid whose density is only about 80% that of liquid water.

The source of this CO₂ is predominantly fossil carbon that is oxidized. (Cement production, as the second most frequent “fossil” source, accounts for just under 4%.) Given the mass ratio of CO₂ to carbon ($44/12 = 3.67$), yearly the global population “burns” just under 8 Gt of carbon. This translates into a somewhat larger mass of fossil fuels as they are hydrocarbons and not pure carbon. In the case of natural gas the multiplication factor is $CH_4/C = 16/12$. For liquid fuels, it is $\sim CH_2/C = 14/12$. For coal, although the factor is expected to be $\sim CH/C = 13/12$, the factor is usually larger because the coal both is wet and contains a noticeable fraction of impurities such as ash.

There are several consequences of the above numbers. First, although we clearly have tremendous amounts of CO₂ to dispose of on a yearly basis, we are already annually handling (pumping, mining, transporting, burning) approximately 1/3 of the required mass in the form of the fuels used to produce the CO₂ (e.g. for CH₂, $14/44 \sim 1/3$). Thus, dealing with the CO₂ is certainly within the realm of possibility. However, on the negative side, CO₂ is not a trace component; in terms of mass, several times more CO₂ comes out of a power plant than goes in the front end as fuel. Volume incompatibilities also arise as a result of the density differences of liquids and solids versus gases. For instance, it is highly unlikely that transportation vehicles will be able to store their own emissions. The volume issue would require that one use a liquid or solid capture agent for the CO₂. This, however, has its own problems, because one would then have to carry both the mass of the CO₂ (already ~ 35 that of the fuel), as well as that of the capture agent, which would likely double the mass value again.

Another common misconception is that one would be able to do anything useful with much or most of the CO₂ generated. In round numbers, the U.S. population of ~ 300 million is responsible for about 6 Gt of fossil CO₂ per year, which yields a yearly average value of 20 metric tons of CO₂ for every man, woman, and child in the nation. Aside from air and water, nothing else is used at that scale. This means that there will be no ability to beneficially use even a substantial

fraction of this CO₂, let alone sell it for a profit. Thus, CO₂ is clearly a waste product whose disposal will have to be paid for.

Now, knowing that the CO₂ will need to be disposed of, one can start to think about possible sinks. Figure 1 shows the various carbon reservoirs on the Earth. Several points are immediately apparent. First, the amount of fossil carbon dwarfs most of the other reservoirs. Second, the commonly proposed “green” solution of increased biomass or even detritus is clearly not the answer in terms of storage because of the amounts of fossil carbon available. There is also the issue of the time frame of such storage. Prior to the industrial age, the biomass and detritus values were quite stable. Hence, if these values were increased through active intervention which then ended, one would expect the values to return to their original preindustrial ones unless the system were actively managed for eternity. At first sight, the only natural system of sufficient scale would appear to be the oceans. However, they too present problems that would prevent their use, because injecting large volumes of CO₂ into the oceans would cause their acidification, with CO₂ forming carbonic acid. Once the ocean pH dropped by 0.3 units, corals—as well as calciferous phytoplankton—would be unable to easily survive because it would become very difficult for them to precipitate their CaCO₃ shells. In fact, only about 1,500 Gt of carbon in the form of CO₂ could be taken up by the oceans before their pH values would decrease from top to bottom by 0.3 units. Interestingly enough, this pH drop would be reached in the surface waters of the oceans rapidly (they are in equilibrium with the atmosphere) when atmospheric CO₂ levels increase to twice the 280 ppm preindustrial value. (This is itself a serious environmental consequence of CO₂ production that is commonly overlooked.) Today, atmospheric CO₂ concentrations have already increased to about 390 ppm. In terms of scale, 1 ppm of CO₂ in the atmosphere corresponds to 2.1 Gt of carbon.

There are a few more counterintuitive chemical issues related to attempting to store CO₂ in the oceans. One involves attempting to bury CO₂ by producing calcium carbonate shells in ocean water. At first glance, this seemingly permanently fixes CO₂ by producing thermodynamically stable CaCO₃ from seawater, whereas in reality it releases CO₂ into the atmosphere. The reason for this is that the CO₂ stored in seawater is dominated by bicarbonate ions; a doubly charged calcium ion holding down two bicarbonate ions. The reaction resulting in the precipitation of calcium carbonate is given by



That is to say, although one CO₂ is permanently sequestered, the removal of the doubly charged calcium ion from the system means that the other CO₂ must be released.

However, if additional calcium (or magnesium) ions are added to the system, net disposal of CO₂ can be achieved. In nature this process occurs very gradually through the weathering of basic minerals. Weathering results in the introduction of additional metal ions to the aqueous system, which can then precipitate the CO₂, thereby yielding vast quantities of mineral carbonates because the oceans are already supersaturated with CaCO₃. In fact, this reservoir of carbon dwarfs all the others because mineral carbonates are thermodynamically stable. It holds about 40 million Gt of carbon, which in turn corresponds to nearly 20 global atmospheres of pure CO₂. This reservoir is also so large that it dwarfs all the fossil carbon that exists, and hence, adding the fossil carbon to this reservoir will have negligible impact on the natural system. Unfortunately, the rate of natural weathering is too slow to deal with the high rate of fossil carbon consumption. However, if an artificial method could be found to increase the rate of weathering, mineralization of CO₂ could become an interesting, permanent, and benign solution.

One other storage approach that could be considered is injecting CO₂ deep underground and trapping it there. Given that there are natural reservoirs of CO₂ and natural gas, which have been stable over geological time, this approach is worth considering. Furthermore, since the entire surface area of the earth is approximately half a billion km², a 1 cm thick shell corresponds to

about 5,000 km³. Thus, there is certainly sufficient volume available to easily hold the CO₂ produced by burning all fossil fuels. The only question is what fraction of the crust is sufficiently gastight to hold the CO₂ for many thousands of years, at a minimum. Unfortunately, that fraction is unknown; the robustness of any random underground location cannot be truly ascertained in advance because of crustal heterogeneity. It can only be determined after injecting high-pressure CO₂. However, given the huge crustal volume available, the problem is simply one of cost, as the CO₂ stored in a leaking site could be withdrawn and reinjected into another site.

If one wants to stabilize atmospheric CO₂ concentrations, one also needs to consider the true scale of the emission reductions needed, as one does not want to pay to halfway fix the problem multiple times. The U.S. population currently generates about 5 times as much CO₂ per person as the average world citizen. If the rest of the world were to move up to our standard of living (and comparable CO₂ emissions) on a per capita basis, then the emissions must drop by a factor of 5 to simply maintain current global emission rates. Furthermore, because the above value is on a per person basis, if the world's population doubles, per capita emission would have to be cut by an additional factor of two. This combined factor of 10 reduction would merely maintain current global emission values in the future. However, at the current global emission rates, atmospheric CO₂ concentrations are increasing. Calculations indicate that emission rate cuts by an additional factor of three from today's values are required to stabilize atmospheric CO₂ concentrations at twice the preindustrial values. Combining all these factors, the result is that U.S. per capita CO₂ emissions to the atmosphere would have to be reduced by a factor of 30 (to about 3% of today's value) to achieve a stabilization of atmospheric CO₂ concentrations at twice the preindustrial values. On an order of magnitude basis, this means our long-term goal needs to be effectively zero emissions. Put in other terms, reductions typically being discussed in public today are woefully inadequate.

One final issue we will consider is that of alternative energy sources. First, let us look at the reasons why fossil fuels are so widely used. There are several primary reasons: 1) fossil fuels are abundant; 2) they are cheap; 3) they have a very high energy density value, both in terms of mass and of volume or "area;" and 4) they are already in a stable stored and storable form. Figure 1 clearly indicates that there are still huge amounts of fossil carbon available. At current yearly consumption rates of 8 Gt, there is still a 1,000-year supply available, if one includes the 5,000 Gt of carbon stored as methane clathrates. Recovery methods will clearly continue to improve, making currently irrecoverable fuels available in the future. Furthermore, well-known chemical routes (water gas production, shift reactions, hydrogasification, Fischer-Tropsch, etc.) make the different fossil fuels (coal, liquid, gaseous) fully fungible, and at prices that are less than the current world market prices of both oil and natural gas. In terms of energy density, a mole of carbon corresponds to roughly 500, 650, and 900 kJ corresponding respectively to 13, 14, and 16 grams of coal, oil, and natural gas. One can appreciate these large values by considering the following. For wind energy, a 1 m² opening with air flowing through it at 10 m/sec (~22 mph) will have 10 cubic meters of air, or about 12 kg, pass through the opening each second. The kinetic energy of that air in 1 second ($\frac{1}{2}mv^2$) is thus 0.6 kJ, clearly a tiny amount compared to the above fossil values.

Furthermore, even at the seemingly "tiny" concentration of 390 ppm, if all the CO₂ from the same 10 m³ of air were to be removed, to replenish it, one would be free to burn enough oil to generate just over 100 kJ of heat, over 2 orders of magnitude more than the 0.6 kJ available from the kinetic energy of the wind per second. (Note that wind power goes as the cube of the wind velocity due to the mass and velocity dependencies.)

A similar comparison is possible for solar energy; the sun providing about 1 kJ/sec (= 1 kW of power) per m² of collection area at the earth's surface under the best conditions. Taking into account that the sun doesn't shine at night and clouds occasionally block the sun, the average solar energy hitting a 1-m² area will be under 0.5 kJ/m²-s even if the collector follows the sun. This power is still roughly comparable to that for wind setups at high wind speeds.

In all these systems, additional conversion efficiency parameters are involved in extracting the raw energy and converting it to a useful form. For example, only ~1/3 of the coal energy is converted to electricity in today's power plants, wind turbines harness ~1/3 of the kinetic energy in the wind, typical user photocells harness only ~10 % of the solar energy (advanced versions now can get ~30%), biomass has a typical efficiency on the order of one to a few percent for converting the raw solar energy into fixed carbon, etc. In Table 1 we compare some of the options for energy generation in terms of needed land areas; the resulting values represent a combination of raw energy densities and conversion efficiencies. The high energy densities and therefore compact areas, volumes, or both involved would seemingly favor fossil fuels by a large margin. The margin is further increased by considerations of cost; the extent of resources available; and the fact that for fossil fuel—unlike solar and wind sources—the energy available does not fluctuate with time. There is, however, the issue of environmental impact, especially when considered over the relevant timescales. For instance, the area needed to generate solar energy is very large. However, if one considers the surface areas that would be “mined” to run power plants for 100 years, the areas involved become roughly comparable. In terms of area, biofuels would by far have the greatest impact. Yet biofuels produced with genetically enhanced photosynthetic efficiency, used to produce “green” oil, and coupled with much-improved vehicle efficiencies and significant electric storage, could replace the need for fossil oil without farming an inordinate amount of the planet. For all the values, it is important to remember that energy consumption is expected to grow considerably in the future.

In conclusion, there are many options available for providing environmentally acceptable energy solutions, provided the scale issues are considered and compensated for up front. At the same time, given the scale of our energy use, any solution will certainly have an environmental impact. The real questions are how small can we make it and how much does it cost.

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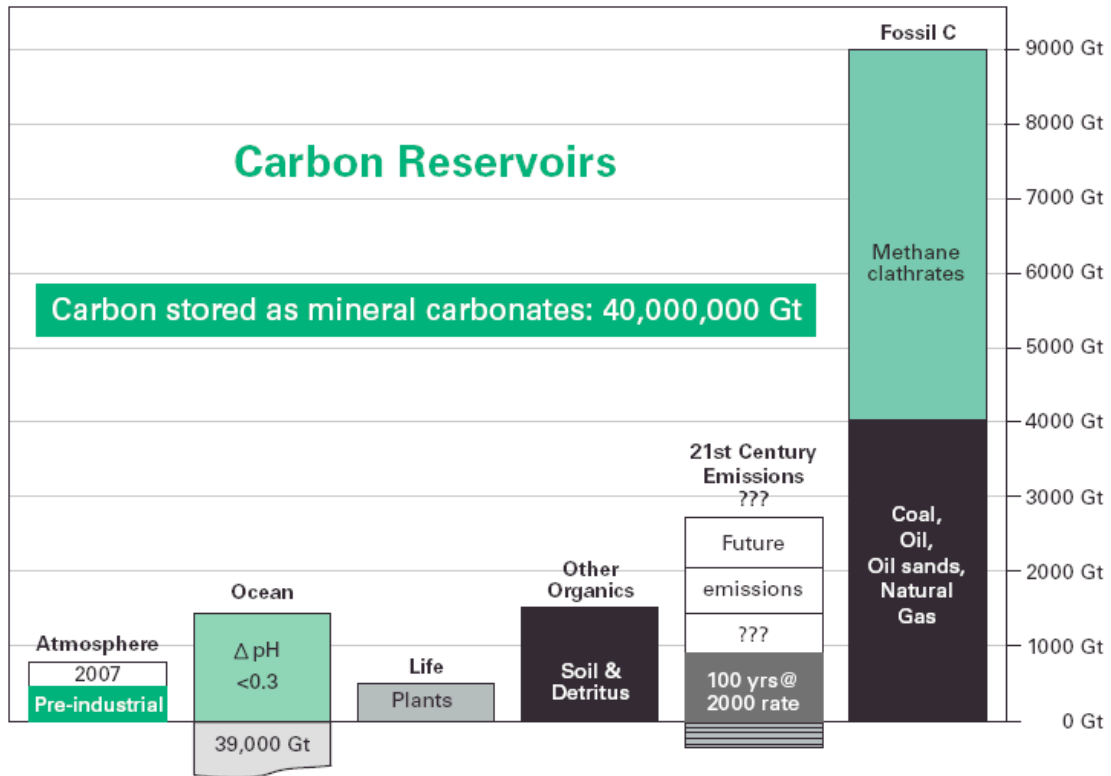


Figure 1. Carbon Reservoirs, Emissions, and Carbon Sinks. The size of various carbon reservoirs and emissions measured in Gt of Carbon. Fossil carbon dwarfs all other reservoirs. The oceans (as a sink) do hold huge amounts of carbon, but they can absorb relatively little without a significant pH change. Emissions for the current century are uncertain, but the first box above the axis shows the emissions that would result from 100 years of fossil emissions at the rate of the year 2000. Clearly several such boxes are expected as indicated. To set the scale, last century we emitted 5 such boxes, but based on the year 1900 values. (These are shown below the horizontal axis.) The Atmosphere column shows that by 2007 we significantly increased atmospheric CO₂ from the preindustrial level.

Table 1. Approximate area required to meet **ALL** of the world's primary annual energy demand in 2007 of 1651012 W-yr. All the values are rough estimates and, depending on assumptions, could easily change by factors of two.

Source	"Raw" power density ⁽⁵⁾ (W/m ²)	Conversion efficiency ⁽⁶⁾	Correction factor ⁽⁷⁾	Actual Area (km ²)	Side of square (km)
Coal ⁽¹⁾ (power plant)	20,000	100.0%	1	800	28
Coal ⁽²⁾ (mined area)	5,545	100.0%	1	2,900	54
Wind (vertical area) ⁽³⁾	600	33.3%	3	26,700	163
Photovoltaic ⁽⁴⁾	200	20.0%	3	133,400	365
Biomass ⁽⁴⁾	200	1.5%	1	5,336,700	2,310
Earth Land Area	NA	NA	NA	148,939,100	12,204

Notes for Table 1

1. This corresponds to the area of the coal plants and their associated on-site coal storage areas.
2. This corresponds to the surface land area of the coal mines to feed the power plants. (A 5 m coal seam thickness is assumed, as is a coal density of 1.4 g/cc, and an energy content of 25 MJ/kg.)
3. This is the vertical area swept by the windmills. The ground area will seemingly be considerably smaller. However, the windmills can't be back-to-back because the air must be remixed with the higher atmosphere in order to reestablish the air speed downstream of the windmills. Thus, the surface area over which the windmills must be distributed will be much larger. There are also concerns about disrupting local weather if wind energy is harvested on the needed scale.
4. This is an average day–night–cloudy sky corrected value and assumes that the sun is not actively followed. The true values do depend on location and time of year, and—in the case of photovoltaic energy—can be larger if the sun is followed.
5. These are the time-averaged power area density values assumed. For the coal cases, the values correspond to the energy generated in a year.
6. Coal is treated as the reference and hence has its conversion efficiency of ~33% already included; the values all refer to primary (e.g. fuel) energy and not—for instance—the electrical power produced.
7. This is a correction to account for the fact that the coal case refers to the fuel energy, not the electric energy produced; whereas, the photovoltaic and wind values are already for electricity because of the conversion efficiency factor. The biomass is assumed to be burned like coal; hence it has a value of 1.