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TO BURY OR TO BURN: OPTIMUM USE OF CROP RESIDUES TO REDUCE ATMOSPHERIC CO₂

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Abstract. We argue that sequestering of carbon waste is inherently more efficient and will probably cost less than using the carbon for biomass burning. The ratio of carbon emitted per unit of primary energy released through combustion, C/E, favors sequestration for fundamental reasons of chemistry and engineering, strongly suggesting a low C/E strategy. This is a more direct way of analysis than assigning dollar estimates to technologies of which we have as yet little or no direct experience.

Crop residues can be a valuable resource for carbon sequestering and/or power generation. How should we assess the relative utilities of the two conflicting uses?

We define residues as organic material remains left behind on fields after harvesting, such as corn stalks and husks. Often this bulk holds more carbon than the crop itself. During a growth season, crops store carbon from air, then exhale it as the crop residues rot, giving no net change in atmospheric CO₂. Rather than letting this carbon rot, one has two choices that reduce net carbon return to the atmosphere:

- (a) burn crop wastes to generate electrical power. This returns all the carbon content to the atmosphere (the same as in just letting it rot), but the power generated lessens the need for power generation through gas/oil/coal-fired plants, thereby effectively reducing overall carbon emissions (Keith, 2001).
- (b) sequester the crop residue and its carbon in such locations as the deep oceans beneath the thermocline, thereby blocking it from reentering the atmosphere for at least centuries (Metzger and Benford, 2001).

Because crop residues can be fuel, Keith (2001) suggests that sequestering wastes is inherently less effective than using it for biomass burning. He assigns dollar costs to the two methods, rather than following the tradeoff between carbon and power.

His argument would only be true if the carbon emitted per unit of primary energy released through combustion, (C/E), was the same for all organic fuels.

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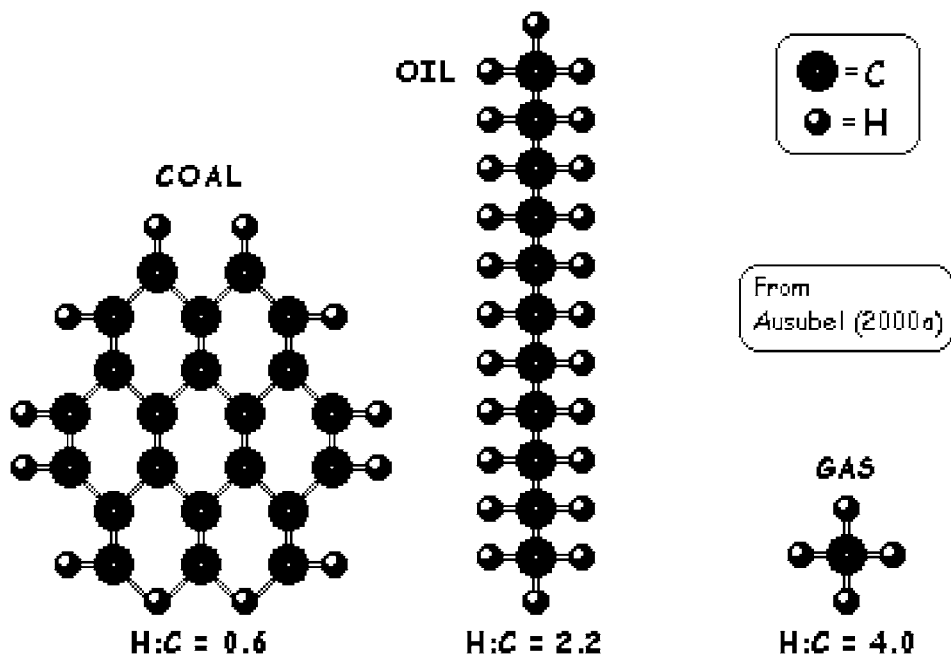


Figure 1. Carbon emitted per unit of primary energy released by combustion (C/E) increases as the $H:C$ ratio decreases – hence the interest in ‘decarbonization’ for carbon dioxide emission reductions. The lowest (C/E) in the fossil fuel family is that of methane, which can be computed from first principles from the heats of formation of reactants and products.

In fact this is not even nearly so. The high (C/E) ratio of crop residue as a biomass fuel produces about *twice as much* atmospheric carbon, compared to a combination of (a) crop residue sequestering, plus (b) production of an equivalent amount of electrical power using a much lower (C/E) fuel such as gas (methane) in a conventional gas-fired plant. This emerges clearly by examining the (C/E) ratios for various organic fuels.

The atomic structures of typical molecules of coal, oil and gas appear in Figure 1 (Ausubel, 2000a). The $H:C$ ratio of coal, oil and gas (methane) are 0.55, 2.2, and 4.0, respectively. The lowest (C/E) ratios are from organic fuels with the highest $H:C$ ratios. As an example, this can be computed from first principles for methane, using the heats of formation of reactants and products in Table I (Glassman, 1977). The heat of reaction for natural gas (methane) combustion can be written:



where from Table I the energy released during combustion of methane, DE , is the difference between the heats of formation of the reactants and the products:

$$DE = [-74.9 - 2(0) + 394 + 2(242)] \text{ kJ/mol} = 803 \text{ kJ/mol}.$$

Table I
Heats of formation at 298.1 K (Glassman, 1977)

Chemical symbol	Name	Mol weight kg/mol	Heat of formation kJ/mol
O ₂	Oxygen (g)	0.032	0.0
CH ₄	Methane (g)	0.016	-74.9
H ₂ O	Water (g)	0.018	-242.0
H ₂ O	Water (l)	0.018	-286.0
CO ₂	Carbon dioxide	0.044	-393.7

Table II
Energy per unit carbon emission (E/C) and carbon emission factor (C/E) for various organic fuels

Fuel	(E/C) TW-yr/GtC	(C/E) GtC/TW-yr
Methane	2.1	0.48
Oil	1.6	0.63
Coal	1.3	0.77
Wood	1.1	0.91

The primary energy per unit carbon emitted (E/C) can be expressed in units of TW-yr/GtC, using the conversion of 1 kJ/mol = 2.62 GW-yr/GtC, in which 1 mole of carbon weighs 0.012 kg. Therefore, the (E/C) ratio for the combustion of methane is 2.1 TW-yr/GtC.

The reciprocal of the (E/C) ratio is the *carbon emission factor*, (C/E). For methane, C/E = 0.48 GtC/TW-yr. Carbon emission factors of oil, coal and wood relative to methane are 1.31, 1.69 and 1.95, respectively (Nakicenovic, 1998). So to produce the same heat as methane, wood releases about twice the carbon.

Table II shows the resulting (E/C) and (C/E) values for various organic fuels. An (E/C) of 1.1 TW-yr/GtC for wood is close to that gotten from the burning or decay of organic matter formed from a photosynthetic process (Bolton and Hall, 1991) of 467 kJ/mol, i.e., a (E/C) of 1.2 TW-yr/GtC.

Figure 2 (Hoffert et al., 1998), illustrates the evolution of global (C/E) over time from 1890 to 2100 according to the IPCC IS92a (business-as-usual) scenario. A (C/E) of 0.91 GtC/TW-yr for biomass burning is 63% higher than the overall average (C/E) from all power generation sources in 1990, and 90% higher than that of gas. That study anticipates that by 2030 the global average (C/E) will fall below

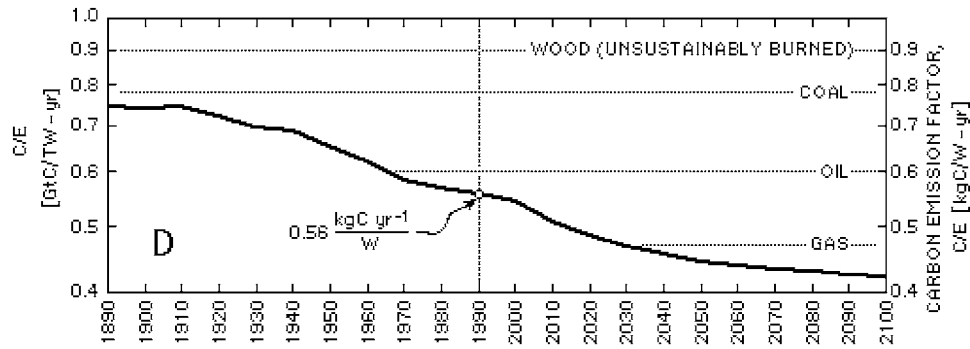


Figure 2. Evolution of (C/E) over time from 1890 to 2100 according to the IPCC IS92a (business-as-usual) scenario. By the year 2030 the C/E of the global energy mix drops below that of natural gas even as coal becomes an increasing fraction of the fossil energy mix. This arises from the basic assumption that we will produce massive amounts of CO₂-emission-free energy. (from Hoffert et al., 1998).

that of gas burning, due to greater implementation of carbon-free emission sources (nuclear, solar and wind).

Biomass (in this case, wood) has such a high (C/E) ratio because it holds much carbon, being mostly a mixture of cellulose (C₆H₁₀O₅) and lignin (C₁₀H₁₃O₄). Ausbel (2000b) showed that an 80% cellulose/20% lignin mixture has an H:C ratio of approximately 0.1 – five times lower than coal, and 40 times lower than methane.

For the same amount of thermal energy released by combustion, crop residue burning leaves in the air roughly twice as much carbon as natural gas burning. Moreover, the global energy mix – already emitting substantially less carbon per unit primary energy liberated than wood burning – may drop below the C/E of natural gas by the year 2030 for a midrange IPCC ‘business as usual’ scenario (Figure 2). This strongly suggests that rather than burning crop residue for power generation, a combination of crop residue sequestering and power generation from lower carbon emission sources is a wiser optimum use of crop wastes. This emerges quite clearly by comparing the use of available crop residues in the United States, for biomass power generation with a combination strategy.

The three principal crops grown in the United States – corn, wheat and soybeans – annually produce nearly 600 Mt of crop residue, containing approximately 250 MtC (Metzger and Benford, 2001). With a (C/E) ratio of 0.91 GtC/TW-yr, this implies that annual crop residue burning could generate 230 GW. Under this scenario, there is no net loss or gain in carbon emissions, since had the crop residue not been used as fuel, it would have rotted and released its carbon into the atmosphere – the same amount of carbon liberated by burning. If, instead of burning the biomass, we permanently sequester it in the deep ocean, we remove 250 MtC from the atmosphere. Using a gas-fired power plant to generate the 230 GW, in which the gas (C/E) ratio is only 0.48, the 230 GW would generate only 132 MtC.

Therefore, while the burning of crop residue produces no *net* carbon emissions, the combination of sequestering and using a gas-fired power plant actually removes [250 MtC–132 MtC] = 118 MtC from the atmosphere, clearly showing the advantages of this approach as compared to crop residue burning.

Globally, about 1.0 GtC may be available in the form of crop residues. (This is about 25% of the 4.1 GtC/yr primary production by agriculture.) If, rather than being burned to produce power (920 GW), these wastes could be sequestered and power generated through a combination of power sources with an average (C/E) of 0.48 (that of gas), then 470 MtC would be annually permanently removed. Currently, our carbon emissions increase atmospheric carbon by 3.5 GtC/year, so removal of 470 MtC would decrease annual atmospheric carbon increase by 13%.

Certainly other effects of dropping crop wastes into the deep ocean must be explored. Nature deposits vast masses of plant debris into the oceans through river runoff, an effect mitigated by natural spreading of ocean currents. Crop waste spreading by varying the dumping site can achieve the same effects at little added cost. Our contribution to the huge stores of natural organics in the deep seas will be much less than 1% over centuries.

There are side issues, as well. The U.S. Department of Agriculture recommends that about a quarter of crop residues be left on the fields to prevent soil erosion and return some nutrients to the soil. This must be balanced against carbon sequestration needs.

Pumping liquid CO₂ below the thermocline differs qualitatively from the crop waste proposal in both chemistry and economics. Such injection schemes may face ecological hazards (Seibel and Walsh, 2001). Certainly liquefying CO₂ and pumping to kilometer depths imposes a large added cost, versus just dropping bales overboard.

We do not address the costs of crop residue transport to deep-sea locations, versus the cost of retrofitting existing power plants to burn crop residues, or the building of crop-residue power plants. These are complicated matters, highly dependent on assumptions. One can tinker with these assumptions to reach just about any economic conclusion one desires (Keith, 2001). To pick merely one facet, it seems likely that moving bales of corn stalks down the vast Mississippi system on barges would cost much less in energy than building and running biomass power plants; but here, the devil is in the details. At this qualitative stage, broad analyses are more useful than attempts to discern the dollar implications of chemical equations.

Rather, we take solely a chemistry and energy perspective, expressed in the C/E ratio. Clearly, a combination of permanent sequestering and the use of low (C/E) ratio organic fuels is the optimum use of crop residues, while their inherently high (C/E) ratios make them a poor choice for power generation.

It seems unlikely that we can get more than 2 TW of carbon-free power from crop waste sequestration plus gas-fired plants, given the waste quantities available. Globally this is a significant contribution toward the 15 TW carbon-free (or more)

that we will need by 2050 for stabilization at twice the present CO₂ level. As well, our scheme does not require appropriation of land from natural ecosystems or farming, and uses simple, inexpensive labor with low capital costs.

References

- Ausubel, J. H.: 2000a, 'Where Is Energy Going?', *Indust. Physicist* **6**, 16–19.
- Ausubel, J. H.: 2000b, 'Letters Section', *Indust. Physicist* **6**, 8.
- Bolton, J. B. and Hall, D. O.: 1991, 'The Maximum Efficiency of Photosynthesis', *Photochem. Photobiol.* **4**, 545–548.
- Glassman, I.: 1977, *Combustion*, Academic Press, NY, p. 5.
- Hoffert, M. I., Caldeira, K., Jain, A. K., Haites, E. F., Harvey, L. D. D., Potter, S. D., Schlesinger, M. E., Schneider, S. H., Watts, R. G., Wigley, T. M. L., and Wuebbles, D. J.: 1998, 'Energy Implications of Future Stabilization of Atmospheric CO₂ Content', *Nature* **395**, 881–884.
- Keith, D. W.: 2001, 'Sinks, Energy Crops and Land Use: Coherent Climate Policy Demands an Integrated Analysis of Biomass', *Clim. Change* **49**, 1–10.
- Metzger, R. A. and Benford, G.: 2001, 'Sequestering of Atmospheric Carbon through Permanent Disposal of Crop Residue', *Clim. Change* **49**, 11–19.
- Nakicenovic, N., Grübler, A., and McDonald, A. (eds.): 1998, *Global Energy Perspectives*, Cambridge University Press, New York, p. 61.
- Schlesinger, W. H.: 1991, *Biogeochemistry*, Academic Press, New York, p. 121.
- Seibel, B. A., and Walsh, P. J.: 2001, 'Potential Impacts of CO₂ Injection on Deep-Sea Biota', *Science* **294**, 319.
- Wyman, C. E., Bain, R. L., Hinman, N. D., and Stevens, D. J.: 1993, 'Ethanol and Methanol from Cellulosic Biomass', in Johansson, T. B. et al. (eds.), *Renewable Energy: Sources for Fuel and Electricity*, Island Press, Washington, D.C., pp. 865–923.

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