The Wedge from Substituting Biomass Fuel for Fossil Fuel

A wedge can be achieved through substituting biomass fuel for fossil fuel

Comments

At least one wedge is probably available from each of two distinctly different strategies involving changes to vegetation. One can enlarge the stock of carbon in vegetation (enlarging the carbon stored in forests, for example), thereby drawing down the stock of carbon in the atmosphere. This topic will be addressed in Section 4 on the Supporting On-Line Material (Forests and Agricultural Soils). It is also possible to replace fossil fuels with fluid fuels produced directly from plant matter (biomass) that is grown sustainably. In the latter case, the use of "biofuels" makes no net addition of CO_2 to the atmosphere; the biofuels oxidized for energy deliberately through technology would have decayed (oxidized) elsewhere anyway (wood on the forest floor, for example). A sustainable biofuel is one obtained from plants that are replaced by new plants at the same rate as they are used.

A hectare of land used to produce biofuels has the potential to have a larger effect on the atmospheric carbon balance than a hectare of land used as a carbon sink. There are two reasons: 1) Most of the new carbon fixed by vegetation each year is allocated to construct short-lived and fast–decomposing tissue, such as leaves and fine roots. Because of its short residence time in ecosystems, such tissue cannot contribute substantially to a carbon sink, but it can be collected and used to produce biofuels. 2) A hectare of land dedicated to biofuels can produce these fuels indefinitely, displacing a stream of fossil carbon indefinitely, whereas a hectare of land used as a carbon sink has a certain capacity to store carbon and then its contribution to carbon accounts "saturates."

Examples of biofuels crops include switchgrass, sugarcane, and corn (S51). A good yield from such annually harvested species is 15 dry tons (dt) per hectare per year. Dry biomass is about 50% carbon by weight, so the carbon yield is 7.5 tC/ha-y, and the yield from 130 million hectares (Mha) dedicated to such biofuels (biofuels plantations) is 1 GtC/y. This is 10 percent of today's 1500 Mha of total cropland.

The energy content of biomass fuel is between 15 and 20 GJ/dt. (The lower value is appropriate for crops, the higher value for wood.) Thus, a good energy harvest is about 200 to 300 GJ/ha-y. This harvest may be restated as 0.7 W/m^2 to 1.0 W/m^2. Comparing this harvest with annually averaged incident sunlight, typically 250 W/m^2, the harvest is seen to convert 0.3 to 0.4 percent of incident sunlight. Such a low conversion rate, even for a high-yield species, is confirmation that the conversion of incident sunlight via photosynthesis has been only one of many objectives of green-plant evolution. Accordingly, there is considerable headroom for genetic engineering to improve substantially on such yields with organisms designed to convert sunlight efficiently into fuel (artificial photosynthesis), greatly reducing the land demands for a future wedge from artificial biofuels, relative to biofuels from nature's plants.

How are biofuels likely to be used? The current energy economy demonstrates clearly that liquid and gaseous fuels that contain carbon are the most valuable forms of energy. We should anticipate that biomass will be transformed preferentially into biofuels, rather than into electricity or hydrogen. As discussed earlier in this Section, biomass conversion into electricity could also become significant, via distributed production and via co-firing with coal. But biomass conversion to hydrogen is unlikely to become important. Hydrogen is not an intrinsically desirable fuel. Its virtue, from a climate perspective is that it does not contain fossil carbon and can be produced with relatively low fossil-carbon emissions. Biofuels already share this virtue[1].

The International Energy Agency estimates that the total energy in biomass providing "primary energy" for human needs in 2000 was 45 EJ, roughly 10% of that year's total primary energy (420 EJ). It further estimates that the non-OECD countries accounted for 85% of this bioenergy (S33, p.411). Most non-OECD bioenergy consumption is "traditional biomass," including firewood, crop wastes, dung, and charcoal. In both the OECD and non-OECD countries, there is a substantial contribution from wood waste in commercial forestry.

Currently, the principal "modern" biofuel is ethanol. In 2002, global fuel ethanol production was 22 billion liters/y, or 380,000 barrels per day, 95% of which was produced in two large national programs: by Brazil (from sugarcane) and by the U.S. (from corn). In both cases, the ethanol is used as automobile fuel, backing out petroleum products. The production rate in Brazil in 2002 for fuel ethanol was 12.6 billion liters/y, or 220,000 barrels per day (S52), about equally in anhydrous and hydrated forms (S53)[2]. The production rate in the U.S. in 2002 was 8.2 billion liters/y (S52), or 140,000 barrels per day[3]. In the U.S., ethanol accounted for about one percent of the energy content of vehicle fuels (S55); it was used in 12 percent of fuel at 10% blend.

Taking 21.1 MJ to be the energy available in a liter of ethanol[4], 0.46 EJ/y is the primary energy production associated with 2002 global ethanol production, which is 1% of all primary biomass energy, and 0.1% of all primary energy. Since ethanol is 52% carbon, a liter of ethanol contains 0.41 kgC[5], and a gallon of ethanol contains 1.55 kgC, about two-thirds of the volumetric carbon content of gasoline or diesel fuel. The current ethanol flow of 22 billion liters per year is a renewable carbon flow of 9 MtC/y, not much larger than the non-renewable carbon flow in Sasol's coal-derived synfuels (7 MtC/y, see

[1] Another "driver" of the energy economy toward hydrogen in many countries is hydrogen's ability to reduce dependence on imported oil and gas, when hydrogen is made from domestic energy sources. Biomass shares this advantage too.

[2] Brazil's 2002-2003 total rate of consumption of ethanol, 12.5 billion liters/y, is the sum of: 1) 5.6 billion liters/y as hydrated ethanol, blended into all gasoline sold in Brazil at a percentage in the low 20s, and 2) 7.0 billion liters/y as anhydrous ethanol, used in engines adapted for pure ethanol (S53).

[3] A different source reports that in 2003 U.S. fuel ethanol production was 10.6 billion liters/y (S54), or 180,000 barrels per day.

[4] The lower heating value (LHV) heat of combustion of liquid ethanol is 26.8 MJ/kg, and its specific gravity is 0.789. Then, the heat released (LHV) in the ethanol combustion 21.1 MJ/liter; equivalently, the combustion of 48 liters of ethanol release 1 GJ.

[5] We again use the specific gravity of ethanol, 0.789.

above). The 2002 renewable carbon flows in Brazil's and the U.S.'s ethanol programs were 5.2 and 3.4 MtC/y, respectively.

Ethanol is currently the principal modern biofuel, because in the natural world there are bacteria that can produce ethanol by fermentation with high selectivity. A world with extensive biofuels production can be expected to produce a wide range of biofuels, including methanol, dimethyl ether (DME), and "biodiesel" fuels[6].

What amount of land produces a wedge, when its harvest of fast-growing biomass is converted to ethanol that backs out conventional vehicle fuels? We assume that ethanol is produced from biomass with 50% energy conversion efficiency. Then, 100 to 150 GJ of ethanol, or 5000 to 7000 liters of ethanol, are produced per hectare[7]. We further assume that engines designed for ethanol, taking advantage of its high octane rating, can convert fuel energy into energy for driving 25% more efficiently than engines designed for conventional fuel, at the same level of engine engineering. Our reference fuel-efficient conventional vehicle, again, is driven 10,000 miles per year with 60 mpg fuel economy, and so uses, annually, 167 gallons of gasoline. The energy content of this gasoline is 20 GJ. Then, annually, the ethanol car will use 16 GJ of ethanol, produced from 32 GJ of biomass. Assuming an average value of 250 GJ biomass yield per hectare, one-eighth of a hectare of dedicated land will be required for each car[8].

Using, as above, 3 kgC/gallon for conventional fuels (which includes 25% carbon overheads in fuels production), the carbon saved annually per car is half a ton. A wedge is the replacement, by 2054, of a fleet of 2 billion reference cars running on conventional fuels by cars fueled by ethanol. The ethanol for a wedge is produced from high-yield energy crops grown on 250 million hectares, an area equal to one-sixth of the world's cropland. It is an ethanol program producing 1000 billion liters of ethanol per year, which is roughly 100 times larger than the current Brazilian or U.S. program, or 50 times larger than the total global program.

Much of the land that would have to be dedicated to annually harvested biofuels crops to gain a wedge would also be suitable for conventional agriculture. Land resources can be stretched by obtaining biofuels from residues of commercial crops (examples include bagasse from sugarcane, corn stover, and rice husks) and from harvest and mill residues of forest plantations.

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[6] The term "biodiesel" is confined to esters of natural vegetable oils. Biodiesel production is expanding rapidly in Europe. An annual biodiesel production capacity of 1.4 billion liters in Europe and 1.5 billion liters globally was in place in 2002 (S52).

[7] This value of ethanol production per hectare per year is similar to Brazil's today from sugarcane, and twice the value in the U.S. today from corn (S52).

[8] The annual carbon flow per car is as follows: one-eighth of a hectare of biomass is, equivalently, 30 GJ, 2 tons, or 800 kgC. From the 800 kgC in biomass we produce 300 kgC in ethanol which backs out 400 kgC in gasoline. Including carbon overheads on the gasoline, 500 kgC of gasoline-related fossil-carbon are not emitted to the atmosphere. (Here, gasoline is 85% carbon, its LHV heat of combustion is 43 GJ/t, and its specific gravity is 0.74.)

Not included here are CO_2 emissions associated with fossil-carbon inputs accompanying ethanol production (inputs for feedstock production and for conversion of feedstock to ethanol). The ratio of fossil fuel input to ethanol output currently ranges from about 10% for Brazilian sugar to near unity for U.S. corn (S52).

Biofuels production has one special feature often mentioned in connection with carbon management: If biomass is co-fired with coal in coal power plants with CCS or in coal-to-hydrogen plants with CCS, the carbon removed from the atmosphere during biomass growth ends up below ground. Via biomass, the atmosphere is scrubbed of CO_2. Atmospheric scrubbing via biomass conversion with CCS is likely to remain a small activity, however, if one accepts that biofuels, not electricity or hydrogen, are the preferred products of biomass production, and that most biomass energy conversion is likely to be at a smaller scale than is required for CCS[9].

Large-scale scrubbing of CO_2 from the atmosphere may be feasible someday, not via storage of CO_2 containing the carbon "captured" by biomass, but via storage of CO_2 captured directly from the air at large dedicated chemical absorption facilities (S56, S57). Such air scrubbing technology, like nuclear fusion electricity, nuclear thermal hydrogen, and artificial photosynthesis, may provide "second-period wedges" in the second half of the century. All of these technologies have the potential to reduce 2104 carbon emissions by 1 GtC/y or more, and to reduce carbon emissions over the interval 2054-2014 by 25 GtC or more, relative to some plausible BAU for 2054-2104. But they probably do not have the potential to provide "firstperiod wedges" in 2004-2054, the subject of this paper. Assigning technologies to "first-period wedges" and "second-period wedges" may be a fruitful exercise.

[9] If the biomass feedstock has a higher C/H ratio than the biofuel product, there may be a CO_2 coproduct. For example, the C/H ratio of biomass – approximately, CH2O – is 0.50, which is higher than the C/H ratio of ethanol (C_2H_5OH), which is 0.33. A simplified ethanol production reaction produces excess CO_2: 3 $CH_2O \rightarrow C_2H_5OH + CO_2 + H_20$. Therefore, biofuels production at very large scale could provide be an opportunity for carbon capture and storage.

References

S33 International Energy Agency, 2002. *World Energy Outlook 2002*. Paris, France: OECD/IEA. By subscription**:** http://library.iea.org/dbtw-wpd/Textbase/nppdf/stud/02/weo2002_1.pdf**.**

S51 Information on fast-growing energy crops may be found an the website of the Bioenergy Information Network, Oak Ridge National Laboratory, Oak Ridge, TN, USA: http://bioenergy.ornl.gov, accessed April 18, 2004.

S52 International Energy Agency, 2004. *Biofuels for Transport: An International Perspective.* Paris, France: International Energy Agency.

S53 "Total Ethanol Production – Brazil – 1990/2002" At the website of UNICA, the Uniao da Agroindustria Canavieiro de Sao Paolo (the Sao Paolo Sugarcane Agroindustry Union), http://www.unica.com.br/i_pages/estasticas.asp, accessed via http://www.portalunica.com.br, April 17, 2004.

S54 See the website of the Renewable Fuels Association**:** http://www.ethanolfra.org**,** accessed 4/18/04. In particular, see http://www.ethanolrfa.org/pr040330.html for U.S. ethanol capacity and http://www.ethanolrfa.org/eth_prod_fac.html for U.S. ethanol production.

S55 U.S. Energy Information Agency, 2004. Table: "Estimated Consumption of Vehicle Fuels in the United States, 1995-2004." http://www.eia.doe.gov/cneaf/alternate/page/datatables/afvtable10_03.xls**.**, accessed April 18, 2004.

S56 Keith, D. W. and M. Ha-Duong, 2003. "CO_2 capture from the air: Technology assessment and implications for climate policy." *Proceedings of the 6th Greenhoure Gas Control Technology Conference, Kyoto, Japan,* J. Gale and Kaya, eds., Oxford, UK: Pergamon, 1661-1664.

S57 Lackner, K.S., et al., 1999. *Proceedings of the 24th International Conference on Coal Utilization and Fuel Systems*, B. Sakkestad, ed. Clearwater, Florida: Coal Technology Association, pp. 885-896.