# GLOBAL WARMING AND THE NEED FOR LIQUID FUELS FROM BIOMASS

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## ABSTRACT

Given the magnitude of the systems which produce global warming and the attendant climate changes, it is important to develop and produce economically-viable carbon reduction technologies which can function on a sufficiently large scale within the next 20 years. Worldwide in 1993 there were 610 million vehicles, with an annual growth rate of 2.7%, or a doubling time of 26 years. Vehicle doubling times for populous emerging economies including China, India, Mexico, and the former USSR range from 6-10 years. Doubling motor vehicle use will add an additional 1 gigatonne C emissions to the atmosphere every year within 15-20 years. In the U.S., switchgrass could be converted to ethanol to produce 50 billion gal of ethanol, or the energy equivalent of 34 billion gallons of gasoline, 25% of 1994 U.S. liquid fuel consumption. The net carbon reduction effect of switchgrass-derived ethanol will depend on the energy sources and requirements for production, distribution and use. The low density of baled switchgrass and the wide geographic distribution of production sites pose problems to be solved, possibly through biomass compaction and large numbers of smaller, geographically distributed ethanol plants. Further development of ethanol separation technologies which use less energy, and technologies to recover and burn biomass lignin are needed to achieve the carbon-reduction potential of ethanol from biomass.

**Keywords:** global warming, climate change, liquid fuels, ethanol, biomass, switchgrass

## INTRODUCTION

Given the magnitude of the systems which produce global warming and the attendant climate changes, it is important to develop economically-viable carbon reduction technologies which can function on a sufficiently large scale. Although the need to reduce the use of fossil fuels is understood, the development and effective deployment of alternative technologies is an immense task, one which will take at minimum a number of decades to carry out. It is moreover a task involving considerable technological, social and economic uncertainties. It will occur during a period of world population growth and potential shortages of water and food, compounded by weather events caused by global warming (Leggett, 1996). Many current and potential technologies will lessen $CO_2$ emissions, but the key question is whether any or all of them can be done on the scale

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necessary to have a significant impact on climate. A key element for effective deployment of technologies is their financial viability over the long term (Hart, 1997). It is highly appropriate to fund R&D, and to subsidize cleaner technologies, e.g. through a carbon tax, but large scale, long term development will require financial self-sufficiency. Development of such technologies will require considerable experimentation and failure as we attempt to find methods which are effective, safe, and have appropriate economic and social tradeoffs.

There is a premium on developing near-term (less than 20 years distant) technologies as global warming and energy use begin to accelerate. There is some evidence that warming can release stored carbon from a large carbon pool in boreal forest soils (Goulden et al., 1998), an instance of positive feedback which could increase the rate of warming. Large forest fires such as those in Indonesia, Mexico and Florida in 1998 provide positive feedback for global warming by quickly releasing carbon stored in living plants, while reducing for some years the leaf area available to sequester atmospheric carbon through photosynthesis. Additionally, atmospheric warming may trigger shifts in oceanic currents and climate which are not quickly reversible ( Broecker, 1997). For these reasons, it is desirable to develop technologies for which there is some existing infrastructure and consumer demand, even though these may eventually be displaced by more sustainable technologies such as solar hydrogen.

The development of biomass technologies offers considerable promise in the near term, with the following benefits: 1) effective recycling of atmospheric $CO_2$, provided production and transportation do not consume excessive amounts of fossil fuels, 2) low cost, current technology to grow and harvest plants, 3) rural jobs, and 4) a fit into currently existing power and transportation infrastructures, specifically the replacement of coal and the use of biomass-derived ethanol to replace gasoline. The development of alternative liquid transportation fuels such as ethanol is particularly important because of the world-wide increase in vehicle miles driven. Potential costs and risks are 1) competition with food crops for land, water and fertilizer, 2) weather impacts, and 3) difficulty in dealing effectively with the low photosynthetic efficiency of plants and the resulting wide land area necessary for sufficient biomass production.

## TRANSPORTATION AND GLOBAL WARMING

In the United States, passenger vehicles and trucks drove 2.4 trillion miles in 1994, more than doubling the vehicle miles travelled (VMT) in 1970. The average annual percentage change in U.S. VMT from 1989-1995 was 2.5%, a rate at which the number of VMT doubles every 28 years. The average annual VMT per vehicle was 11,700 miles, and average fuel consumption was 695 gallons in 1994, with a total fuel consumption of 140 billion gallons of gasoline and diesel fuel. U.S. passenger cars drove 67% of the VMT with an average fuel mileage of 9.14 km/l (21.5 mpg), with light trucks adding another 25% at 6.63 km/l (15.6 mpg)(American Automobile Manufacturers Association, 1996). Worldwide, in 1993 there were 465 million passenger cars and 145 million commercial vehicles in use, totalling 610 million vehicles, with an annual growth rate of 2.7%, or a doubling time of 26 years (United Nations, 1995). The United States had about 1/3 of these, totalling 194 million vehicles. Roughly another 1/3 were owned by western European countries and Japan.

Growth rates in vehicle ownership are higher in emerging economies, which translates into shorter doubling times. Statistics by country from the United Nations and the American Automobile Manufacturers Association show this clearly. Total vehicles in use in millions from the latest data available (1992-1994) and doubling times in years calculated for the preceding 5-7 years are: China, 9.5 million (6 yr doubling time); India, 6.2 (7 yr); Mexico, 12.3 (11 yr); former USSR, 11.5 (10 yr); Poland, 8.1 (9 yr); Turkey, 3.1 (6 yr); South Korea, 7.4 (3 yr) (American Automobile Manufacturers Association, 1995; United Nations, 1995). Thus developing and newly industrializing countries have much shorter doubling times for vehicle ownership, reflecting both rising personal income and starting from a smaller base number of vehicles relative to the population size. It is likely that the world average growth in ownership and VMT will tend toward these higher growth rates. Given the data cited, a world doubling time for vehicle ownership seems likely to move down from the current 26 years to 15-20 years.

Starting with 610 million vehicles in 1993 and conservatively assuming the current growth rate of 2.7%/yr, there should be 680 million vehicles in 1997. After a 15-20 year doubling time, there would be 1,360 million vehicles in the world. Assuming the average vehicle travels 16,000 km (10,000 miles)/yr, this would total 14 trillion VMT worldwide by 2012-2017. If the average fuel mileage is 8.5 km/l (20 mpg), this would consume 2.6 trillion liters (680 billion gal) of fuel. Assuming for simplicity that all of this is gasoline, and that each gallon produces a total of 22.5-22.9 lb $CO_2$ from production, combustion and distribution (Environmental Protection Agency, 1990; Energy Information Administration, 1996), this would amount to 8 billion short tons of $CO_2$ per year. Using a conversion of 1 tonne C /4.041 short tons $CO_2$ (Wuebbles and Edmonds, 1991), this is equivalent to 2 gigatonnes of carbon emissions. The current carbon flux from all fossil sources is about 6 gigatonnes C/yr (Brown et al., 1997). Doubling motor vehicle use will add an additional 1 gigatonne C/yr to the atmosphere every year within 15-20 years.

In principle, electric vehicles using electricity derived from solar energy could lessen the overall $CO_2$ emissions from vehicular transportation. However, electric vehicles currently face two severe limitations. First, the current electric power grid derives most of its energy from fossil fuels: coal, oil and natural gas, with most of the rest coming from nuclear plants and hydropower. Second, batteries for electric vehicles have a low specific energy, or energy per unit mass, compared to liquid fuels. The specific energy storage of gasoline is at least an order of magnitude greater than batteries made with current technology (Policy Implications of Greenhouse Warming, 1992).

Given the current manufacturing and fuel distribution infrastructure, and the inherent specific energy advantages of liquid fuels, internal combustion vehicles running on liquid fuel are likely to be prevalent over the next 10-20 years, and we need to address solutions which take account of this reality. Ethanol produced from cellulosic biomass has the potential to significantly reduce greenhouse gas emissions (Interlaboratory Working Group, 1997). Moreover, vehicles which can utilize ethanol as E85 are available today.
Ford has sold more than 12,000 Flexible Fuel Vehicles (FFVs) since 1993. These run on

either E85, unleaded gasoline or a mixture of the two, controlled by a sensor in the fuel system (Ford Motor Company, 1998). Ford plans to produce 250,000 FFVs over a 4-year period, and Chrysler will offer cars and vans capable of using E85 (Governors' Ethanol Coalition, 1997a). In the summer of 1997, 68 E85 filling stations were operating in the U.S., with another 113 planned to open by 1999 (Governors' Ethanol Coalition, 1997b). A recent DOE study estimates a market potential of 5 billion gallons of ethanol by 2010, assuming its use as a gasoline blending component only (Interlaboratory Working Group, 1997). The further development of E85 vehicles and the use of ethanol as a fuel for hybrid electric vehicles could increase this market further.

## SOURCES OF ETHANOL

### Current Ethanol Technology

The ethanol industry in the United States is likely to require significant technological change if it is to remain viable and grow over the next 10 years. In 1994, about 1 billion gallons of ethanol was used in gasoline in the U.S. Ethanol production capacity in January 1996 was about 1.5 billion gallons, including ethanol used for beverages and solvents as well as transportation fuel. Approximately 95% of this ethanol was produced from corn, with a yield of about 2.5 gallons of ethanol per bushel of corn. From 1988 to 1995, ethanol production used about 7% of the U.S. average annual corn production.

The profitability of ethanol production in the United States depends on the prices of corn as an input, the prices of the products: ethanol and DDGS (distiller's dried grains and solubles) used as livestock feed, and federal and state subsidies for ethanol. Apart from political uncertainties over subsidies, the major risk to profitable ethanol production is the price of corn. In essence, it is unprofitable to make ethanol from corn when the price of corn exceeds $4.00-$4.50 per bushel, given current subsidy levels. In the summer of 1996, corn prices went briefly over $5.00 per bushel, compared to an average price of $2.30/bushel for 1988-1995, and ethanol prices also increased to $1.50-1.80/gallon (Chemical Marketing Reporter, 1996). In Minnesota, at the peak price of corn, the net profit per gallon of ethanol produced was negative $0.42/gallon (not counting the Minnesota state subsidy of $0.20/gallon). Without the federal gas tax credit for ethanol, it would have been negative $0.96/gallon (Office of the Legislative Auditor, 1997).

This corn price spike illustrates the vulnerability of corn-based ethanol from an economic point of view. Firstly, 1 billion gallons of ethanol provided approximately 0.1% of the United States' energy needs in 1994, compared to 39% from petroleum (Office of the Legislative Auditor, 1997). Expanding this ethanol contribution to 1% would consume 70% of the U.S. corn crop and raise the price of corn. Secondly, corn prices are likely to rise due to increasing exports. China alone is projected to have a grain production/ consumption deficit of 100 million tons in 2000, and 200 million tons in 2010 (Brown, 1995). Every demand increase of 100 million bu of corn raises the price by $0.05/bu . An additional annual demand of 100 million tons of corn, or 3600 million bu/year, could lead to a price increase of 36 x 0.05 or $1.80/bu by the year 2000, assuming no additional sources of supply. The historical average price of corn from 1989-1996 is $2.55/bu (Office of the

Legislative Auditor, 1997). Thus corn could cost \$2.55 + 1.80 or \$4.35/bu by the year 2000, clearly at the margin of profitability for low-volume (current) ethanol production with subsidies. Many factors influence this hypothetical calculation, including weather events and increased food demand from countries other than China (Brown, 1995). In any case, expanding ethanol production to a level which could substitute for a significant fraction of current U.S. gasoline use would raise corn prices, with corn feedstock prices becoming a limiting factor at some point.

## Ethanol from Lignocellulosic Biomass

A potential solution to this problem is a change to cellulose-based ethanol production using herbaceous energy crops (HEC) or short rotation woody crops (SRWC) as feedstocks (Lynd et al., 1991; Wyman et al., 1993). These materials consist of cellulose and hemicellulose, which can be hydrolyzed to yield glucose and pentose sugars, which can be used as fermentation substrates for ethanol. In addition, lignocellulosic biomass contains lignin, which can serve as a boiler fuel for process heat or electricity generation. Much research has been supported by the U.S. Department of Energy (DOE) at the National Renewable Energy Laboratory (NREL) and the Oak Ridge National Laboratory (ORNL) on the economics, growth, harvesting and conversion of lignocellulosic biomass to ethanol (Graham, 1994; Wright, 1994; McLaughlin et al., 1996).

Switchgrass is a tall perennial grass which grows from Canada to Central America . Substantial research has been done on the economics, breeding, cultivation and harvesting of switchgrass for use as an energy crop ( Wright, 1994; Taliaferro and Hopkins, 1996; Teel, 1996). Switchgrass requires lower fertilizer inputs than corn, for example nitrogen at 50 kg/ha/yr vs. 135 kg/ha/yr for corn (Ranney and Mann, 1994). This lowers costs, reduces runoff pollution, and saves on energy costs and carbon emissions associated with fertilizer production. Switchgrass can produce 1 or 2 crops per year, every year, in contrast to short rotation woody crops, which are harvested every 4-6 years, and conventional forests, which may need 10 years or more between harvests. Grasses are potentially better able to adapt to climate change than forests, a factor which may be important in the future (Bright, 1997).

As a perennial grass, switchgrass can be harvested by mowing, leaving the roots in place to hold the soil. It is used as a ground cover on erosion-sensitive lands and is drought-tolerant. An analysis at ORNL (Graham, 1994) estimates that 54 million hectares (133 million acres) of land in the U.S. are suitable for switchgrass production, but marginal for conventional annual crops such as corn. This land could yield 696 million Mg (767 million tons) of dry herbaceous biomass per year at an average yield of 12.9 Mg/ha (5.8 tons/acre). If this amount of switchgrass were entirely converted to ethanol at a yield of 280 liters/Mg (McLaughlin et al., 1996), this would produce 195 billion liters (51 billion gal) of ethanol, or the energy equivalent of about 34 billion gallons of gasoline. This is approximately 25% of 1994 U.S. liquid fuel consumption. Ethanol/ gasoline equivalents are based here on energy contents of 76,100 Btu/gal for ethanol and 113,537 Btu/gal for gasoline (Interlaboratory Working Group, 1997) for an energy equivalence ratio of 0.67. For engines optimized to run on ethanol, this ratio increases to 0.8 (Lynd et al., 1991).

Other estimates for U.S. cellulosic biomass capacity are higher. Lynd et al. (1991) estimate a cellulosic ethanol production potential of 12.4-26.5 quad (1 quad = $10^{15}$ Btu) or 160-350 billion gal/yr based on cellulosic wastes, idled and potential cropland and forest land. Using an estimate of 77 million ha and a yield of 20 Mg/ha, Wyman et al. (1993) project a U.S. energy crop capacity of 1.5 billion Mg/yr. Adding to this MSW, underutilized wood and crop residues, they project a total of 2.3 billion Mg of cellulosic feedstock/ yr, potentially producing > 1 trillion liters (260 billion gal) of methanol and ethanol annually (yield assumed is 430 l/Mg or 103 gal/ton).

Hall et al. (1993) estimate a global potential for plantation biomass (wood and grass) of 890 million hectares, with a potential yield of 15 Mg/ha (6.7 tons/acre). This is probably an upper limit, equivalent to 10% of the land area presently in cropland, forests, woodland and pasture, or 7% of the total world land area. This quantity of biomass would provide energy exceeding 260 exajoules/yr, or more than 80% of global commercial energy use in 1985. If entirely converted to ethanol at 280 l/Mg, it would yield 3.7 trillion liters (1 trillion gal), the energy equivalent of about 670 billion gal of gasoline.

## PROBLEMS AND SOLUTIONS

Biomass-derived ethanol meets the criterion of being potentially deployable on a large enough scale to have an impact on the fossil-fuel carbon emissions which cause global warming, and it has a significant current technology base with many opportunities for future improvement. Large-scale deployment and commercial success for switchgrass-derived ethanol will require solutions to problems in at least two areas: (1) the low density of baled switchgrass, and (2) the energy required to separate ethanol from a dilute fermentation solution.

Plants have a low photosynthetic efficiency, meaning that the amount of incident solar radiation fixed into chemical bonds is relatively low, resulting in a fuel product which has a lower energy per unit volume than coal or oil. The practical implication of this is that a wide land area including many production sites will be needed to produce enough biomass to achieve a significant reduction in carbon emissions. The wide geographic distribution of production sites, combined with the low density of baled switchgrass creates a need for transportation of large amounts of biomass. Transportation using trucks powered by fossil fuels (diesel) creates greenhouse gases and adds to the cost of delivered feedstock.
For example, 6'x5' round bales of switchgrass have a density of 133 kg/m$^3$. A truck with a volume of 35 m$^3$ could carry about 4.66 metric tons of switchgrass. Assuming an ethanol yield of 280 liters/metric ton (67 gal/ton)(McLaughlin et al., 1996), this amount of switchgrass would produce 1300 liters of ethanol, occupying a volume of 1.3 m$^3$, giving a volumetric ratio of switchgrass to ethanol of about 27. Put another way, it takes 27 truckloads of switchgrass to produce one truckload of ethanol. This volumetric ratio problem is more severe for low-density biomass than for corn. Assuming a yield of 2.6 gal ethanol /bushel of corn, the comparable volumetric ratio is about 3.6:1.

Possible ways to reduce biomass transportation energy and storage costs are:
a) Compaction or densification using mechanical pressure to reduce the volume of a given

quantity of biomass (KTBL, 1984; Ortiz et al., 1996) . Large-scale transportation and storage of biomass will probably require some form of compaction. Densified biomass would also be more suitable for lower cost means of transport such as rail or barge. This is useful also for coal substitution in power generation. Problems to be solved are throughput and the energy required.

b) Large numbers of smaller, geographically-distributed ethanol plants, so that large numbers of truck trips carrying switchgrass bales are replaced by fewer truckloads of ethanol out and chemical inputs in. Current thinking is that larger corn-based ethanol plants are more efficient, because of factors such as the more efficient use of labor and capital, and opportunities for reuse of process heat. A change to biomass-based ethanol plants will need to take into account the transportation volume problem noted above, and to consider the possible advantages of smaller biomass ethanol plants deployed in greater numbers. Problems to be solved are economies of scale vs. transportation costs, development of efficient and economically viable process technologies, personnel for small plants, automation and control, waste disposal, and safety.

Ethanol purification requires considerable amounts of energy, whether the ethanol is derived from corn or biomass. Possible ways to reduce energy use and net carbon production associated with ethanol purification are:
a) Distillation and separation technologies which use less energy per gallon of ethanol produced.
b) Recovering and burning lignin to produce process steam and electricity. Apart from the potential reduction of carbon emissions, lignin use technologies could substitute at least partially for the value of coproducts created by wet mill and dry mill corn ethanol plants.

Solving these problems could be of significant benefit to establishing a new and larger non-fossil ethanol industry in the United States, with the potential to export technology and components to other countries. Deployment of these technologies on a sufficiently large scale could significantly reduce the net carbon emissions from the transportation sector.

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