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6. AUTHOR(S)
Robert H. Borgwardt, Meyer Steinberg and Yuanji Dong

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. EPA
Research Triangle Park, NC 27711

Brookhaven National Laboratory
Upton, NY 11973

Hydrocarb Corporation
New York, NY 10018

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REDUCTION OF CO_2 EMISSIONS FROM MOBILE SOURCES BY ALTERNATIVE FUELS DERIVED FROM BIOMASS

Robert H. Borgwardt[1], Meyer Steinberg[2], Yuanji Dong [3]

(1) U.S. Environmental Protection Agency, Research Triangle Park, NC 27711
(2) Brookhaven National Laboratory, Upton, NY 11973
(3) Hydrocarb Corporation, New York, NY 10018

ABSTRACT

The U.S. needs an alternative transportation fuel that can displace 30 percent of petroleum fuels by the year 2010, as called for by the Energy Policy Act (PL102-486). The Act, promulgated in October, 1992, seeks an alternative that will reduce greenhouse gas emissions as well as improve the national economy by reducing oil imports. This paper examines the prospects for achieving those goals with alcohol fuels derived from biomass produced as short-rotation woody crops. Emphasis is on the Hydrocarb process, now under evaluation by the EPA for production of methanol from biomass and natural gas. Factors considered in this evaluation include: land requirements, feedstock costs, conversion yield of fuel per unit of biomass, cost per unit of fuel energy produced, and equivalent cost of gasoline displaced. The analysis indicates that a process such as Hydrocarb, that can leverage biomass with natural gas, should maximize petroleum displacement at least cost. Because of these advantages, it may also achieve greatest reduction of greenhouse gas emissions from the transportation sector.

REDUCTION OF CO_2 EMISSIONS FROM MOBILE SOURCES BY ALTERNATIVE FUELS DERIVED FROM BIOMASS

INTRODUCTION

Several recent events have begun to focus attention on alternative transportation fuels in the U.S. The Clean Air Act, as amended in 1990, provides an initial impetus for the production of clean fuels such as ethanol, methanol, and reformulated gasoline in order to reduce toxic emissions in urban areas. The National Energy Strategy (U.S. Department of Energy, 1991) showed that an alternative fuel of some kind will be needed in large amounts by year the 2000 due to declining petroleum reserves. Specific requirements for identifying the best alternative fuel for broad use were outlined in the Energy Policy Act of 1992 (U.S. Congress, 1993) which establishes goals of 10 percent displacement of petroleum by year the 2000 and 30 percent by the year 2010. According to the Act, the desired alternative should have maximum displacement of oil imports and greatest benefit to the national economy. Most importantly to the present discussion, the Act also specifies that greatest reduction of greenhouse gas emissions should be achieved. Since CO_2 is the predominant greenhouse gas emission associated with use of automotive fuels, the focus of this paper is the reduction of CO_2 emissions from the transportation sector.

Criteria that must be taken into account when evaluating potential alternative fuels are there-fore: the extent to which petroleum might be replaced, the degree to which greenhouse gas emissions might be reduced, and--as always--the cost of production. It would also be preferable, if possible, that it be liquid, compatible with the existing refueling infrastructure, and producible from domestic resources, and that it reduce the toxic emissions associated with petroleum fuels. In the near term, the most practicable approach for reduction of greenhouse gas emissions from mobile sources is a fuel derived from biomass, produced on a renewable and sustainable basis. As summarized in Table 1, a number of processes can produce alcohol fuels from biomass, the most promising of which, from the standpoint of cost, are the enzymatic hydrolysis process for production of ethanol and the Battelle Columbus Laboratory (BCL) process for production of methanol by indirect gasification of biomass. Both of those processes are intended to utilize as feedstocks cellulosic biomass cultivated as short-rotation woody crops (SRWC) to be harvested every 3-4 years for the specific purpose of conversion to liquid fuels.

In 1990, the Brookhaven National Laboratory proposed to the Environmental Protection Agency another route for production of methanol from woody biomass using natural gas as cofeedstock. The potential advantages of the process, in addition to cost, are higher yield of alcohol fuel from a given biomass supply and

Table 1. Options for Producing Alcohol Fuels from Biomass

Process	Alcohol production cost, $/GJ (LHV)	Reference
Ethanol by acid hydrolysis	24.4	Wright *et al.*, 1985
Ethanol by enzymatic hydrolysis (cellulose)	22.3	Wright, 1988
Methanol by steam-oxygen gasification	13.4	Reed, 1981
Ethanol by fermentatiion of corn	13.3	Jones, 1989
Ethanol by enzymatic hydrolysis (cellulose + xylose)	11.1	Wyman *et al.*, 1992
Methanol by indirect gasification (BCL process)	9.6	Larson and Katofsky, 1992

therefore a greater displacement of petroleum. To the present time, the EPA has been supporting theoretical and experimental studies of the process, called Hydrocarb, that are summarized in this paper and compared with the best alternatives of Table 1 in terms of the principal criteria for evaluating those alternatives, beginning with production cost.

BIOMASS COST

For most biomass conversion processes, the cost of feedstock is the dominant factor affecting the production cost of alcohol fuels. The cost of biomass is the sum of its poduction and transport costs. Data published by Strauss et al. (1989) for least-cost SRWC production in the Pennsylvania area is given as $65.71/(dry)Mg. The cost of cultivating the biomass was given by Strauss in 1989 as $35.41/(dry)Mg; more recent data (Strauss et al., 1990) show a reduction in cultivation cost to $32.40/(dry)Mg for an optimized, 3-year rotation period with fertilization. Assuming a chipping cost of $6.80/(dry)Mg as reviewed by Kenney (1991), the breakdown of current production costs is shown in Table 2.

Table 2. Breakdown of Production Costs for Woody Biomass

	$/(dry)Mg
Cultivation	32.40
Harvest/baling	8.00
Loading/unloading	4.20
Chipping	6.80
Other	3.00
Wet storage	10.20
Total production cost	$64.60

The Table 2 estimate can be compared with others obtained from different test sites such as the values published by Perlack and Ranney (1987) which averaged $62.87/(dry)Mg for six regions of the U.S. and Ismail and Quick (1990) for poplar tree plantations in Canada. A value of

$63.70/(dry)Mg is therefore assumed here as representative of the current SRWC production cost.

An examination of biomass transport costs in the U.S. was recently published by Bhat et al. (1992) which are given as:

$$\text{U.S. dollars/(wet)Mg} = (3.65 + 0.62d)/18.14 \qquad (1)$$

for woody crops, and

$$\text{U.S. dollars/(wet)Mg} = (34.08 + 0.62d)/15.42 \qquad (2)$$

for herbaceous crops, where d = the round-trip distance (km) between farm and processing plant (or twice the mean farm-to-plant radial distance).

The moisture content of fresh cut biomass is generally about 50 percent. If, as is true in many cases, the biomass yield per hectare and the production cost of herbaceous crops are similar to woody crops, it is clear from the above equations that woody crops will provide feedstock at least cost for biomass delivered to large energy conversion plants.

Delivered Cost of Biomass

The delivered cost increases with transport distance which is a function of the size of the biomass supply region from which the feedstock is obtained. Since the size of that supply region is a function of the plant size, one must begin with a choice of plant size in order to calculate a methanol production cost. The delivered costs of biomass for plant sizes corresponding to 9090 and 5300 (dry)Mg/day at a 90 percent operating factor are presented in Table 3. Selection of these plant sizes is based on available data that will be used for estimating Hydrocarb costs and comparing them with other published data, to be discussed later.

Given a biomass production cost of $63.70/(dry)Mg, we assume that the biomass supply region consists of three concentric sectors surrounding the plant site (Figure 1): the nearest

sector contains 18 percent of its total area dedicated to plantations producing SRWC; that sector is surrounded by a second sector containing 9 percent of its area dedicated to SRWC, and the third, outermost, sector of the supply region has 3 percent of its area planted in SRWC. In accordance with the current range of SRWC yields obtained in research field trials (Wright et al., 1992), the productivity is assumed to be 11 (dry)Mg/ha-yr in each sector with 90 percent recovery of the biomass produced.
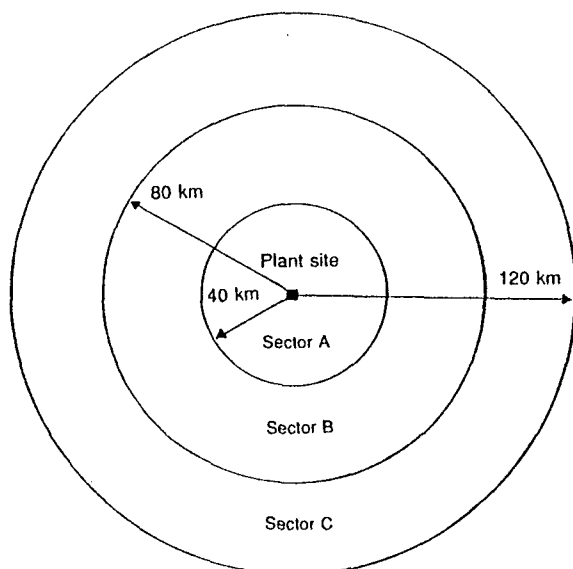

Figure 1. Assumed layout of biomass supply region for 9090 (dry)Mg/day energy conversion plant

These assumptions yield the results shown in Table 3 which indicate that transport cost will add 10-13 percent to the cost of biomass production. These delivered costs of feedstock will be used to compare alcohol production costs for the process options.

THE HYDROCARB PROCESS

The Hydrocarb process, conceived at the Brookhaven National Laboratory, has been under evaluation by the EPA (Steinberg et al., 1991; 1993) as a new source of transportation fuel that could reduce CO_2 emissions from mobile sources and meet future needs for a clean alternative fuel on a large scale. The optimum flow sheet, developed by computer simulations to maximize methanol yield and minimize cost, is illustrated in Figure 2. Biomass and natural gas are fed to a gasifier operating at 800°C to produce methane in an exothermic reaction with recycled hydrogen. The gasifier effluent is pyrolyzed to hydrogen and CO in a second reactor at 1100°C, and methanol, the desired product, is synthesized in a third reactor by conventional catalytic technology. The entire system operates at 50 atm pressure. The principal differences between this and other biomass/ methanol processes, from the equipment stand-point, is the recycle of excess hydrogen to the gasifier, the recovery of thermal energy from the high-temperature step, elimination of a shift converter, and elimination of cold gas cleanup to remove CO_2, sulfur, and volatile alkalies. From the process standpoint, the main difference is the incorporation of natural gas as cofeedstock to enhance the production of methanol synthesis gas. Table 4 summarizes performance estimates obtained from the process simulations.

Development Status

The performance estimates of Table 4 assume chemical equilibrium in each process stream, as given in Figure 2. The degree to which the performance estimates can be attained will be

Table 3. Delivered Cost of Woody Biomass, Including Production and Transport

	Size of energy conversion plant, (dry)Mg/day	
	5300	9090
Maximum radius of biomass supply region, km	91.7	120
Production cost, $/(dry)Mg	63.70	63.70
Average transport cost (eq. 1), $/(dry)Mg	7.39	9.56
Total delivered cost, $/(dry)Mg	71.26	73.43

CO 5.46
CO_2 3.3
CH_4 17.45
H_2O 0.03
H_2 64.72
N_2 8.02
CH_3OH 1.0

Purge gas 0.19 kg mol

H_2O 9.0 kg

DRYER — Wood 100 kg 11.8% H_2O

Steam 50 kg 268°C

CH_4 40 kg

HYDRO-GASIFICATION REACTOR 800°C — 958°C — 21.8 kg mol — 50°C — CONDENSER 50°C — CH_3OH 165.8 kg

Char & Ash 6.3 kg

CO 6.78
CO_2 3.28
CH_4 30.92
H_2O 16.24
H_2 36.54
N_2 6.1
28.95 kg mol

HEAT EXCHANGER

CO 4.99
CO_2 3.03
CH_4 15.95
H_2O 0.78
H_2 59.17
N_2 7.34
CH_3OH 8.74
66.09 kg mol

38.44 kg mol

METHANE PYROLYSIS REACTOR 1100°C — 1100°C — 582°C

METHANOL CONVERTER 260°C — 519°C — 260°C

Carbon 8.54 kg

CO 18.64
CO_2 0.4
CH_4 9.97
H_2O 2.8
H_2 63.58
N_2 4.59
38.44 kg mol

Alumina

BOILER

Flue gas

COMBUSTOR 1400°C

Purge gas 0.19 kg mol
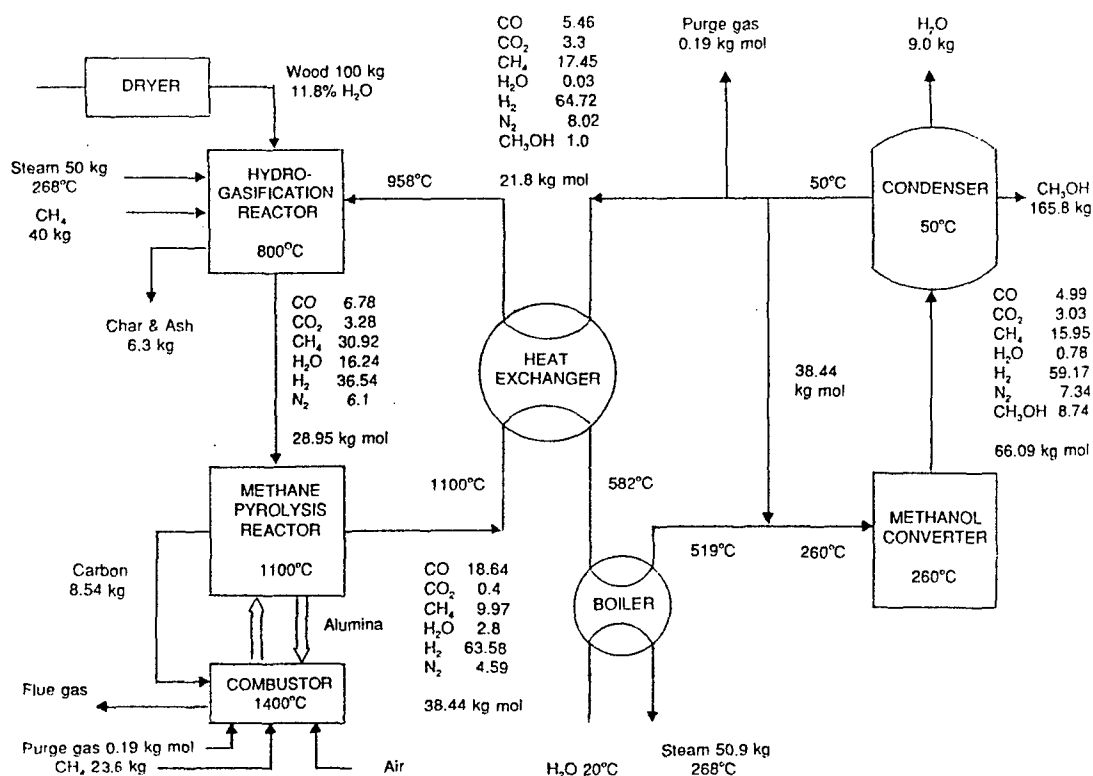CH_4 23.6 kg
Air

H_2O 20°C

Steam 50.9 kg 268°C

Figure 2. Flow sheet for production of methanol from biomass and natural gas.

Table 4. Performance Estimates for the Hydrocarb Process

Mols methanol/mol biomass fed	1.36
Mols methanol/mol CH_4 fed	1.30
Gasifier throughput, kg-mol/liter of methanol product	0.139
Net CO_2 emission, mol/mol of methanol produced and utilized	0.631
Thermal efficiency, %	67

determined in bench scale tests of the reactor hardware soon to be undertaken by the EPA with funds from the Strategic Environmental R&D Program of the Department of Defense, and co-sponsorship with the California South Coast Air Quality Management District. The 50-atm methanol synthesis step and the biomass gasification step, including control of alkali volatiles and entrained particulates, are within the current state of the art. The other principal step, methane pyrolysis, is not. The pyrolysis reactor requires indirect heat transfer with inert solids recirculated at high volume between the fluidized bed reactor and an external combustor/riser. Although many aspects of the required pyrolysis system have been operated successfully in the Cogas process (Hebden and Stroud, 1981) and the Universal Oil Products catalytic hydrocarbon cracking process (Pohlenz and Scott, 1966), none has been operated at the pressure and temperatures required by Hydrocarb. Substantial engineering challenges must therefore be met, begining with choice of materials and extending to control of heat carrier attrition, refractory erosion, high temperature gas/solid separation, high pressure combustion of carbon black, and isolation of combustion gases from the process stream.

Economic assessment

Our estimate of the capital cost of a Hydrocarb plant is obtained from a comparative analysis based on the detailed evaluation of the Texaco coal gasification, dedicated methanol plant that was prepared by Fluor Engineers and Construc-

tors, (Buckingham *et al.*, 1981). That plant, operating at a gasifier pressure of 59 atm, produces 1.25×10^7 liters/day of methanol with a gasifier throughput of 0.158 kg-mol per liter of methanol product. We take credit for the absence of an air separation unit in Hydrocarb and partial credit for the shift converter and Selexol gas scrubbing units. The Texaco system, which is equivalent to a Hydrocarb plant processing 5300 (dry)Mg/day of biomass, was estimated by Fluor to require a plant facilities investment (PFI) of 1.076×10^9 in 1979 dollars. With the appropriate credits, adjusting for differences in throughput, and accounting for inflation (by a factor of 1.55), we estimate the PFI for Hydrocarb at 1.057×10^9 in current dollars.

Our economic evaluation assumes operating and maintenance (O&M) costs to be slightly lower than Texaco's 6 percent of PFI which included a singificant cost for disposal of coal ash. Due to the low ash content of biomass, Hydrocarb O&M is calculated to be 5 percent of PFI, or 1.609×10^5/day for a 5300 (dry)Mg/day plant.

Total capital investment (TCI) is normally about 125 percent of PFI (and is the case for Fluor's Texaco evaluation). Therefore, it is assumed here that the TCI (which includes allowance for funds during construction, working capital, land, royalties, etc.) for a 5300 DMT/day Hydrocarb plant will be $10.57 \times 10^8 \times 1.25 = \$13.21 \times 10^8$ in current dollars.

Alcohol Production Cost Estimate

The cost of producing methanol in a 5300 (dry)Mg/day Hydrocarb plant from biomass with a delivered cost of $71.26/(dry)Mg is calculated as follows, assuming a 6% capital charge rate and 15% return on investment:

From the material and energy balances of the process simulation, 63.6 Mg of CH_4 feed is required per 88.3 (dry)Mg of biomass feed. At a cost of $2.50 per 1000 ft^3 (28.3 m^3), the daily cost of natural gas feed for this Hydrocarb plant will be:

$$\frac{63.6 \times 22400 \times 2.5 \times 5300}{88.3 \times 16.043 \times 28.32} = \$470,500/\text{day}$$

The daily operating costs are then:

Biomass $5300 \times 71.26 =$	$377,680
Natural gas $=$	$470,500
O&M: $0.05(10.57 \times 10^8)/365(0.9) =$	$160,880
Capital charge:	
$0.06(13.21 \times 10^8)/365(0.9) =$	$241,300
Total daily operating cost	$1,250,400

From the material and energy balances, 165.8 kg of methanol is obtained from 88.3 kg of biomass and 63.6 kg of CH_4, therefore the cost of production (C_p) for 15% return on investment is:

$$C_p \times \frac{165.8 \times 5300 \times 1000 \times 2.205}{88.3 \times 8.34 \times 0.796} -$$

$$1,250,400 = \frac{0.15 \times 13.21 \times 10^8}{365 \times 0.9}$$

Giving $C_p = \$0.561/\text{gallon}$ or $9.36/GJ (LHV).

Comparison with Other Alcohol Processes

Cost estimates for the production of ethanol and methanol from biomass by other routes have recently been published. In the case of ethanol, the estimates are given for the enzymatic hydrolysis process for two plant sizes, 1745 (dry)Mg/day and 9090 (dry)Mg/day (Wyman *et al.*, 1992). Methanol costs were recently reviewed by Larson and Katofsky (1992) for four biomass gasification processes rated at 1650 (dry)Mg/day plant size; of those methanol processes, the BCL indirectly heated gasifier was shown to yield significantly lower production cost than the others. The result of Larson and Katofsky's evaluation of the BCL process is summarized in Table 5 together with the above data for Hydrocarb and the data for the two enzymatic ethanol systems evaluated by Wyman *et al.*

Table 5. Cost Estimates for Production of Alcohol Fuels from Biomass

	Hydrocarb methanol	Enz. Hydrol. ethanol		BCL methanol
Plant size, (dry)Mg/day	5300	1745	9090	1650
Plant facilities investment (PFI), millions of US$	1057	128	432.75	152
Total capital investment (TCI), % of PFI	125	123	124	146
O&M, % of PFI[a]	5.0	4.5	4.5	7.0
Total operating cost[b], millions of US$/yr	53	17.8[c]	66[c]	13.5
Capital charge rate, %	6	6	6	6
Return on investment, %	15	7	7	16
Alcohol production, millions of liters/yr	4100[d]	219[e]	1096[e]	333[d]
Biomass cost, US$/(dry)Mg	71.26	46	46	37.6
Plant operating factor, %	90	90	90	90
Alcohol production cost, $/GJ (LHV)	9.36	13.12	11.06	9.62

[a]Excluding catalysts (enzymes)
[b]Excluding feedstock
[c]Including credit for exported electricity
[d]99+% CH_3OH; less than 0.75% H_2O
[e]90.3% C_2H_5OH; 4.7% H_2O; denatured with 5% gasoline

It is clear from Table 5 that a comparison of alcohol production costs requires normalization of their implicit assumptions regarding plant size, return on investment, and biomass cost. The data were therefore recalculated for a common plant size of 9090 (dry)Mg/day and 7 percent ROI using scaling factors that duplicate the results of the ethanol scaleup from 1745 to 9090 (dry)Mg/day according to the following procedure:

$$\text{TCI for 9090 (dry)Mg/day plant} = \text{TCI} \times (9090/\text{plant size})^{0.744}$$

and: $\text{O\&M cost for 9090 (dry)Mg/day plant} = \text{O\&M} \times (9090/\text{plant size})^{0.8}$

Figure 3 shows the resulting relationship between alcohol production cost at the plant gate and the delivered cost of biomass when the data of Table 5 are normalized to the same assumptions. At the expected cost of biomass delivered to a plant of this size, $73.4/(dry)Mg (Table 3), the comparison suggests that Hydrocarb may produce alcohol fuel at a cost about half that of
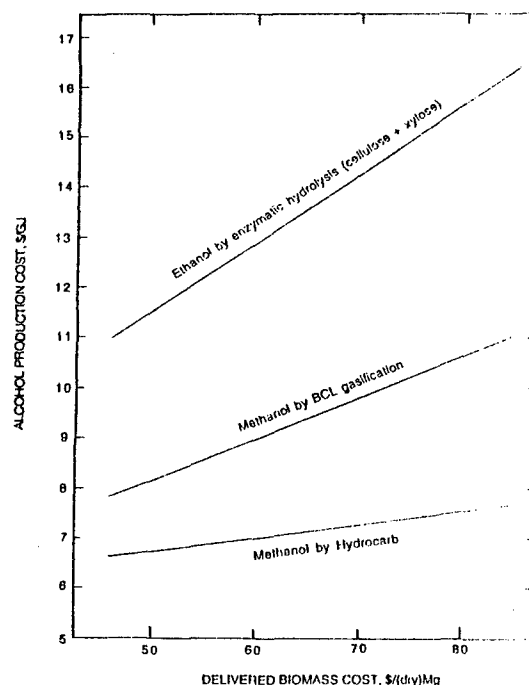

DELIVERED BIOMASS COST, $/(dry)Mg

Figure 3. Comparison of alcohol production costs for 9090 (dry)Mg/day energy conversion plants with 7 percent return on investment.

the best ethanol process and about 25 percent less than the best alternative methanol process. It is also significant that Hydrocarb is less sensitive to the cost of biomass than the other processes, due mainly to the fact that natural gas is a lower cost feedstock than biomass, and also because a higher yield of alcohol is obtained per unit of biomass fed.

Ethanol forms an azeotrope containing 10.7 mol percent water which is difficult to separate, and further refinement is not attempted for the enzymatic process. Fuel grade ethanol consequently contains 4.7 wt percent water after gasoline is added as a necessary denaturant. Methanol does not form an azeotrope with water and does not require a denaturant. Fuel grade methanol will therefore be essentially pure CH_3OH.

Equivalent Gasoline Price

Following the calculation procedure outlined above, but assuming a 9090 (dry)Mg/day plant size and 15 percent ROI, the cost of methanol production by Hydrocarb is is calculated to be $0.526/gal (3.79 liter). The equivalent gasoline price can be obtained by adding the marketing costs as specified by the Office of Technology Assessment (U.S. Congress, 1990): $0.08 for markup, $0.06 for distribution, and $0.12 for taxes per gallon of methanol and multiplying by the volumetric equivalence ratio of methanol/gasoline. Assuming an equivalence ratio of 1.57 for vehicles optimized for neat methanol, the equivalent gasoline price is:

$$(\$0.526 + 0.08 + 0.06 + 0.12)1.57 = \$1.23/gal \qquad (3)$$

In 1992, the average price of gasoline in the U.S., weighted according to the amount of each grade sold, was $1.19/gal. One can therefore conclude that Hydrocarb methanol would cost about 4 cents per gallon more than the current gasoline price. With or without the energy tax now being considered by the Congress, if methanol can be produced at the projected costs, it should be competitive with current gasoline prices.

The volumetric ratio of 1.57 used in eq. 3 assumes a 27 percent improvement in fuel economy for methanol vehicles, due to its higher thermal efficiency in internal combustion engines. This ratio is obtained from tests performed by the EPA Office of Mobile Sources (U.S. EPA, 1989) on conventional vehicles powered with neat methanol. Those vehicles employed some; but not all, of the characteristics that take advantage of methanol's chemical and combustion properties which make it an inherently more efficient fuel than gasoline. The most important of those properties are its higher octane rating, which allows a higher compression ratio, its wide flammability limits, which permit good combustion at high air-to-fuel ratios, and its higher power output, which allows the use of a smaller, more efficient engine. Two converted gasoline engines (EPA, 1989) and two modified diesel engines (Bruetsch and Hellman, 1992) have been tested with an overall average improvement of 27 percent in thermal efficiency. Most other performance comparisons reported in the literature were obtained with vehicles designed for gasoline or M85, which give poorer performance than can be expected when both the engine and vehicle are designed specifically for use with neat methanol. Although no vehicle has yet been designed to take advantage of all properties of M100 as its intended fuel, the best data available to date indicate that such vehicles can achieve at least 27 percent improvement in thermal efficiency relative to gasoline.

Effect of Future Cost Escalations

We have assumed the current price of natural gas to be $2.50/10^6 Btu (1.06 GJ) in the above cost comparisons. This is representative of the current price, but it has recently been as low as $1.10/10^6 Btu in some areas of the U.S. The sensitivity of the Hydrocarb methanol poduction cost to the price of natural gas is shown in Figure 4 for a 9090 (dry)Mg/day plant and 15 percent ROI. The price of natural gas is expected to increase in the future with the price of other energy sources, particularly crude oil. The Gas Research Institute (GRI)(Dreyfus and Koklauner, 1992) project a 38 percent escalation of the crude oil price in constant 1992 dollars by
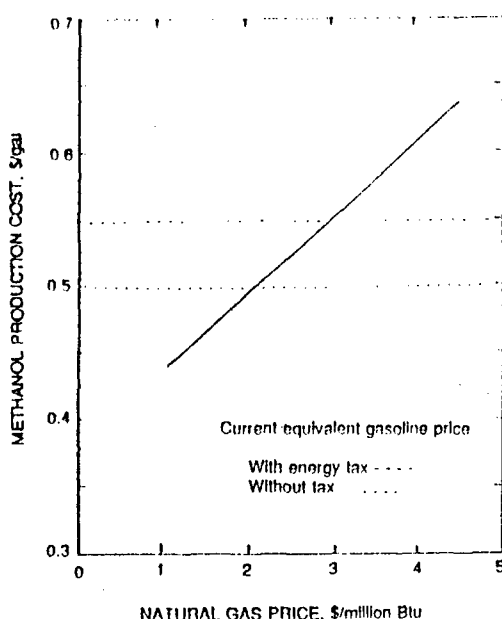
Figure 4. Estimated methanol production cost as a function of the price of natural gas; plant size = 9090 (dry)Mg/day, biomass = $73/(dry)Mg, return on investment = 15%.

year 2010. It may be assumed that the price of natural gas will escalate by the same amount, from $2.50 to $3.45/10^6 Btu by the year 2010. If we use this value for the price of natural gas and assume that the real cost of biomass does not escalate (it may in fact decrease in constant dollars if projected improvements of yield, genetics, and cultivation practices are realized), then the cost of Hydrocarb methanol in the year 2010 would increase from the current value of $0.526 to $0.580/gal which is equivalent to a gasoline price of $1.32/gal.

GRI's projection of the average retail gasoline price for year the 2010 is $1.58/gal in constant dollars. Assuming no energy tax on gasoline in the year 2010, the cost of methanol would be $0.26/gal less than the equivalent price of gasoline. The projected trends therefore favor methanol as a cheaper fuel than gasoline.

IMPACT ON PETROLEUM DISPLACEMENT AND GREENHOUSE GAS EMISSIONS

The Energy Policy Act of 1992 (U.S. Congress, 1993), is intended to promote the replacement of petroleum motor fuels with alternative fuels to the maximum extent practicable and to ensure the availability of the alternative that will have greatest impact on reducing oil imports, improving the national economy, and reducing greenhouse gas emissions. It establishes numerical replacement goals of 10 percent by year 2000 and 30 percent by 2010.

Alcohol fuels derived from domestically produced biomass and competitive with petroleum fuels would significantly benefit the national economy if 30 percent of the petroleum requirement could be displaced. Not only would oil imports be reduced, but many jobs would be created within the U.S. industrial and farming sectors. As indicated by Figure 3, methanol is likely to be the least costly alcohol option and, if produced by Hydrocarb, the most competitive with gasoline. If successfully developed, Hydrocarb methanol should be less costly than petroleum fuels by year 2010.

Lowest cost is of little importance, however, if the available biomass cannot be converted into sufficient amounts of fuel to substantially offset the needs of the transportation sector. Table 6 compares the amount of alternative fuel that could be produced from one tonne of biomass, the corresponding gasoline displacement, and the CO_2 reduction from a vehicle fleet, if that biomass were converted to alcohol by one of three process options. On this basis of comparison, Hydrocarb would more than triple the amout of gasoline displaced by conversion of the biomass to liquid fuel. The last column of Table 6 indicates the amount of methanol that could be produced from the natural gas (720 kg/tonne of biomass) that is required for Hydrocarb if that gas were used in a seperate plant to produce methanol by the conventional steam reforming process. Thus, if one considers the BCL process supplemented by a conventional methanol plant, the comparison indicates that the two processes would displace 12 percent less gasoline, and obtain 49 percent less CO_2 reduction, than a single Hydrocarb plant . The improved technology option for ethanol production assumes that a large increase in biomass conversion efficiency can be achieved,

Table 6. CO_2 Reduction Potentials from one Tonne of Biomass

| | Alcohol production technology | | | | |
| | Ethanol by enzymatic hydrolysis | | Methanol by BCL gasification | Methanol by Hydrocarb | Methanol from natural gas[a] by steam reforming |
	(current)	(improved)			
Alcohol produced, kg-mol	5.7	8.8	18	59	34
Gasoline displaced, gal	70	108	125	410	230
Net CO_2 eliminated, kg	630	970	1130	2490	87

[a]Assuming that the natural gas used for Hydrocarb is converted to methanol in a separate plant.

together with a major reduction of capital cost for the enzymatic process. The comparison with that option in Table 6 indicates a Hydrocarb advantage of 20 percent more gasoline displacement and 135 percent more CO_2 reduction.

As suggested by Table 5, earlier estimates of alcohol production costs from biomass generally assumed plant sizes ranging from 1500 to 2000 (dry)Mg/day. In order to displace 30 percent of the petroleum requirement in year the 2010 (about 7.5 EJ) with biomass conversionplants of that size, the number of plants necessary would be unrealistically large as indicated by Table 7. Biomass conversion plants as large as 9090 (dry)Mg/day may still be of questionable practicalness for processes other than Hydrocarb because of the large numbers of plants required.

One must also consider the amount of land in the U.S. that is suitable for the production of woody biomass as short rotation crops in dedicated energy farms. That area, not essential for food crops, has been conservatively estimated (Graham *et al.*, 1992) to be 14 million ha which

could yield about 3 EJ of wood energy. An optimistic estimate of the maximum SRWC energy yield is 12 EJ (Lee *et al.*, 1991). Given the projected alcohol yields from the leading process options, Table 8 shows the percent of highway fuel consumption in the year 2010 that could be replaced. Should the lower estimate of biomass availability prove correct, the comparison indicates that no more than 7 percent displacement of petroleum could be obtained as ethanol, whereas Hydrocarb could displace the full 30 percent with that minimum amount of biomass. Should the 12 EJ estimate accurately represent the total biomass potential, much of that land will nevertheless be too distant from an energy conversion plant to permit its use for biomass farming. In any case, it is clear that only methanol could meet the projected goal of 30 percent displacement and, it were produced by Hydrocarb, could in theory displace all of the transportation fuel requirement in the year 2010. As a practical matter, it is unlikely that either the biomass supply or alcohol production capacity for 100 percent displacement could be in place by the year 2010.

Table 7. Number of Energy Conversion Plants Required to Produce 30 Percent of U.S. Hwy Fuel Requirements in Year 2010

| Plant size, (dry)Mg/day of biomass | Number of plants producing fuel by: | | |
	Enzymatic hydrolysis	BCL biomass gasification	Hydrocarb
1,700	1705	1110	235
9,090	340	208	44

Table 8. Percent of Highway Fuel Consumption in Year 2010 that could be displaced by Biomass Derived Fuel

Available biomass supply, quads	Biomass conversion technology			
	Enzymatic hydrolysis (current)	(improved)	BCL biomass gasification	Hydrocarb
2.5	4	6	8.8	30
9	14	21	31	100
12	18	28	42	

CONCLUSION

The Energy Policy Act provides a strong incentive for identification of an alternative fuel that can best meet future demands for displacement of petroleum, improving the national economy, improving urban air quality, and reducing greenhouse gas emissions. Based on the assumptions made, this analysis suggests that methanol has greater potential than ethanol for meeting national goals for alternative fuel production, in terms of both the amount of petroleum that could be displaced and the cost of production. Among methanol production options, the Hydrocarb process presents a prospect for maximum displacement of petroleum and greatest reduction of greenhouse gas emission from mobile sources. The large potential effect of alternative fuel production on the national economy implies the use of domestic resources as feedstock to the maximum possible extent and therefore favors biomass produced in a renewable and sustainable manner such as SRWC. Because of the limitation of biomass supply it will be essential to leverage that feedstock with another domestically available feedstock to meet the projected alternative fuel requirements. Since natural gas is a cofeedstock for the Hydrocarb process, the amount of liquid fuel that can be produced from the limiting resource is increased substantially. This analysis projects that Hydrocarb has the potential to yield methanol at a cost lower than the future cost of gasoline. Although development of the Hydrocarb process will challenge the state-of-the-art in several respects, the projected advantages form the basis for the EPA program

to fully evaluate its potential in a systematic development effort.

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