# Methanol Production from Biomass and Natural Gas as Transportation Fuel

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Two processes are examined for production of methanol. They are assessed against the essential requirements of a future alternative fuel for road transport: that it (i) is producible in amounts comparable to the 19 EJ of motor fuel annually consumed in the U.S., (ii) minimizes emissions of criteria pollutants, (iii) reduces greenhouse gas emissions from production and use, (iv) is cost-competitive with petroleum fuel, and (v) is compatible with the emerging vehicle technologies, especially those powered by fuel cells. The methanol yield, production cost, and potential for reduction of overall fuel-cycle $CO_2$ emissions were evaluated and compared to those of reformulated gasoline. The results show that a process utilizing natural gas and biomass as cofeedstocks can meet the five requirements more effectivly than individual processes utilizing those feedstocks separately. When end-use efficiencies are accounted for, the cost per vehicle mile traveled would be less than that of gasoline used in current vehicles. $CO_2$ emissions from the vehicle fleet would be reduced 66% by methanol used in fuel cell vehicles and 8–36% in flexible-fuel or dedicated-methanol vehicles during the transition period. Methanol produced from natural gas and biomass, together in one process, and used in fuel cell vehicles would leverage petroleum displacement by a factor of about 5 and achieve twice the overall $CO_2$ emission reduction obtainable from the use of biomass alone.

## Introduction

In response to increasingly severe effects of air pollution on human health and the environment, ambient air quality standards were established by the Clean Air Act of 1970, and stringent vehicle tailpipe emission standards for CO, $NO_x$, VOC, and particulate matter ("criteria" pollutants) were promulgated by amendments to the Act in 1990. Motor vehicle emissions nevertheless continue to be the largest single source of air pollution in the U.S. Recognizing the implications of an increasing population of motor vehicles and the growing dependence on imported petroleum to fuel them, the National Energy Strategy of 1991–92 called for the development of clean alternative fuels derived from domestic resources, including renewable biomass, to begin displacing petroleum. The Energy Policy Act of 1992 established a goal of 30% displacement of petroleum with alternative fuels by the year 2010, with half of that fuel to be derived from domestic resources. Although the Act identifies no specific alternative fuel as a preferred choice, three objectives were given: (i) achieve maximum replacement of imported petroleum, (ii) maximize the benefit to the national economy by minimizing the total cost to the nation, and (iii) reduce the environmental impacts of fuel production and use, including greenhouse gas emissions that may affect future climate change.

$CO_2$ released from production and use of transportation fuels represents about 30% of the U.S. total anthropogenic greenhouse gas emissions and must therefore be an essential part of any climate-change mitigation strategy. The long-term risks associated with climate change were cited as one of the most serious issues facing the Environmental Protection Agency (EPA),[1] and efforts to displace petroleum with fuels having less effect on atmospheric $CO_2$ accumulation were recommended as a preemptive action—justified regardless of uncertainties of the effects of climate change—because the improved air quality and reduced dependence on imported oil are valuable benefits that are independently justified. Recent assessments of R&D needs in the transportation sector[2-6] conclude that the existing technology is unsustainable due to its long-term impacts on the environment, human health, the natural ecology, and climate change. Emissions of air pollutants and greenhouse gases are consistently cited in those assessments with regard to the nonsustainability of the current system of road transport that is based on internal combustion engines and petroleum fuels. Thus, an alternative vehicle/fuel system must be sought that can reduce both regulated air pollution and greenhouse gas emissions.

Natural gas (NG) is a clean alternative fuel that can reduce vehicle emissions of both the criteria pollutants and $CO_2$ (NG emits 14 kg of carbon/GJ; oil emits about 20 kg of carbon/GJ). The Climate Change Action Plan of 1993 directed the EPA to promote NG as a transportation fuel under the provisions of the Clean Air Act, which regulates the criteria pollutants, to reduce emissions of unregulated $CO_2$ also. The Plan—like the Energy Policy Act and the National Energy Strategy—further encouraged the introduction of renewable sources of transportation fuel energy, including biomass such as wood, carbonaceous wastes, and energy crops. Given these national objectives, the question addressed in this paper is how NG and biomass resources can be utilized most effectively at least cost.

Methanol is a clean, proven vehicle fuel that can be produced from NG gas and does not have the refueling

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problems that limit the acceptance of NG. It can also be produced from biomass and thus has potential to reduce greenhouse gas emissions and help displace oil imports with a domestic source of fuel energy. The economics of producing methanol from natural gas have been assessed by Lange[7] for current technology in developed and remote sites having NG prices of $2.0 and $0.5/GJ, respectively. He showed that existing routes of production, assuming the value of methanol as vehicle fuel to be a function only of its energy content relative to that of petroleum in a free market, cannot compete with gasoline until, or unless, the crude oil price increases to about $27/bbl. A difficulty with assessing the value of alternative fuels based on their competitiveness with gasoline is the fact that the market price of petroleum fuels does not include the external costs associated with their use. Such externalities include the real, but difficult-to-quantify, costs of the sustainability issues outlined above. Estimates of the external cost of petroleum fuels used in U.S. gasoline and diesel vehicles range from 4.9 to 36.5 cents/gal, and the cost of the air pollution impacts of motor vehicle emissions is another 26 cents/gal to $3.1/gal.[8] It is essential, therefore, that the full future costs and benefits of vehicle/fuel systems, including the reduction of $CO_2$ emissions, be recognized when assessing those technologies if they are to be relevant to the long-term issues of sustainability and useful for comparison with other mitigation strategies for greenhouse gases.

Another factor that must be recognized when comparing the costs of methanol and gasoline is the variable end-use efficiency of fuel/vehicle systems. The value of an alternative fuel must account for the relative efficiency by which its energy can be extracted by different vehicle technologies. Due to its favorable chemical and combustion properties, methanol is about 27% more efficient in a dedicated internal-combustion-engine vehicle (ICEV) than gasoline,[9] which substantially reduces the oil price at which it could compete with gasoline. In the coming decade, fuel cell vehicles (FCVs) are expected to enter the commercial market having fuel efficiencies 2–3 times greater than gasoline used in current vehicles. The effectiveness of methanol as a hydrogen source for FCVs as well as its compatibility with ICEVs during the transition to FCVs is an essential advantage. FCVs powered with reformulated gasoline or other hydrocarbons may also become available, and may be initially dominant, though less effective in addressing the sustainability problem. The question that must be answered in terms of the national interest for future road transport is the cost of each fuel relative to gasoline in terms not only of production cost but also of cost per vehicle mile traveled in the most efficient vehicle that can use it—with external costs included.

Technologies for producing methanol exclusively from biomass have been evaluated by Katofsky;[10] of the five gasifier options he considered, the Battelle–Columbus Laboratory (BCL) system was determined to be most economical and will be the basis for comparisons considered here. Marrison and Larson[11] estimated the cost of methanol production from short-rotation woody crops by a BCL plant of optimum size to be $12.6/GJ HHV ($14.5/GJ LHV). This optimum plant size (7870 metric tons/day biomass) was determined by balancing increased plant size, which reduces production cost due to economy of scale, and the size of the biomass supply

area, which increases with plant size and thus increases the delivered cost of feedstock.

Assuming a crude oil price of $20/bbl, which is representative of the average over recent years, the production cost of regular gasoline is about 60 cents/gal.[12] An additional 5 cents/gal is required to reformulate gasoline to meet air quality standards in populated areas. If gasoline is to be used in FCVs, its current sulfur content of 340 ppm must be reduced by at least an order of magnitude, adding another 6 cents/gal to the cost. The total production cost of a clean, low-sulfur gasoline is therefore about 70 cents/gal or $5.8/GJ LHV.

Considering only its energy content, methanol produced from biomass alone at $14.5/GJ cannot compete with the $5.8/GJ production cost of gasoline. A second barrier to this route is the fact that the amount of biomass that could be produced in the U.S. on land available and suitable for that purpose is not sufficient to displace a major part of the current fuel energy requirement for road transport or significantly reduce $CO_2$ emissions from that source.[13] Both barriers may be overcome by using NG as cofeedstock with biomass, which increases methanol yield, improves biomass conversion efficiency, and reduces production cost. That is the approach examined here.

**Procedure**

When thermally integrated to provide the energy needed for biomass drying and crude methanol distillation, the BCL process produces 16.09 kg-mol of methanol/1000 kg of biomass with a thermal efficiency of 60% excluding imported electric power; if the extra electric power is produced from biomass, the methanol yield is 14.77 kg-mol and the net thermal efficiency is 51%.[13] Conventional steam reforming yields 0.782 mol of methanol/mol of total NG used as process feedstock and fuel[14] with 63.6% thermal efficiency. Using these values as benchmarks for production of methanol independently from biomass and NG, respectively, the methanol yield and production efficiency of two methods of using NG as cofeedstock with biomass were evaluated and compared assuming the same amounts of feedstocks for each case. The two cases to be examined are (i) a modification of the BCL process and (ii) the Hynol process.

The following general procedure applies to both process evaluations. The same process assumptions were applied as those of Katofsky,[10] where applicable, and consistent values of input variables, including biomass composition, biomass carbon conversion, plant size, reactor approach to equilibrium, mechanical efficiencies, heat recovery efficiencies, and equipment costs. Material and energy balances were prepared with the process engineering simulator Aspen Plus, thermally integrating and optimizing each system to avoid import of electric power and provide sufficient process steam and other energy for refining methanol to 99.5 mol % and drying biomass from 48 to 10 wt % moisture. A biomass composition (weight basis) of 45.97% C, 6.73% H, 46.38% O, 0.14% N, 0.07% S, and 0.71% ash, including moisture, was assumed. A typical NG composition was also assumed: 94.7 mol % $CH_4$, 2.8% $C_2H_6$, 2.3% $N_2$, and 0.2% $CO_2$.

Reforming is carried out at 950 °C with a steam/carbon ratio of 2.5 entering the reformer. Methanol is synthesized at 260 °C by an isothermal reactor cooled by steam generation. Equilibrium assumptions were
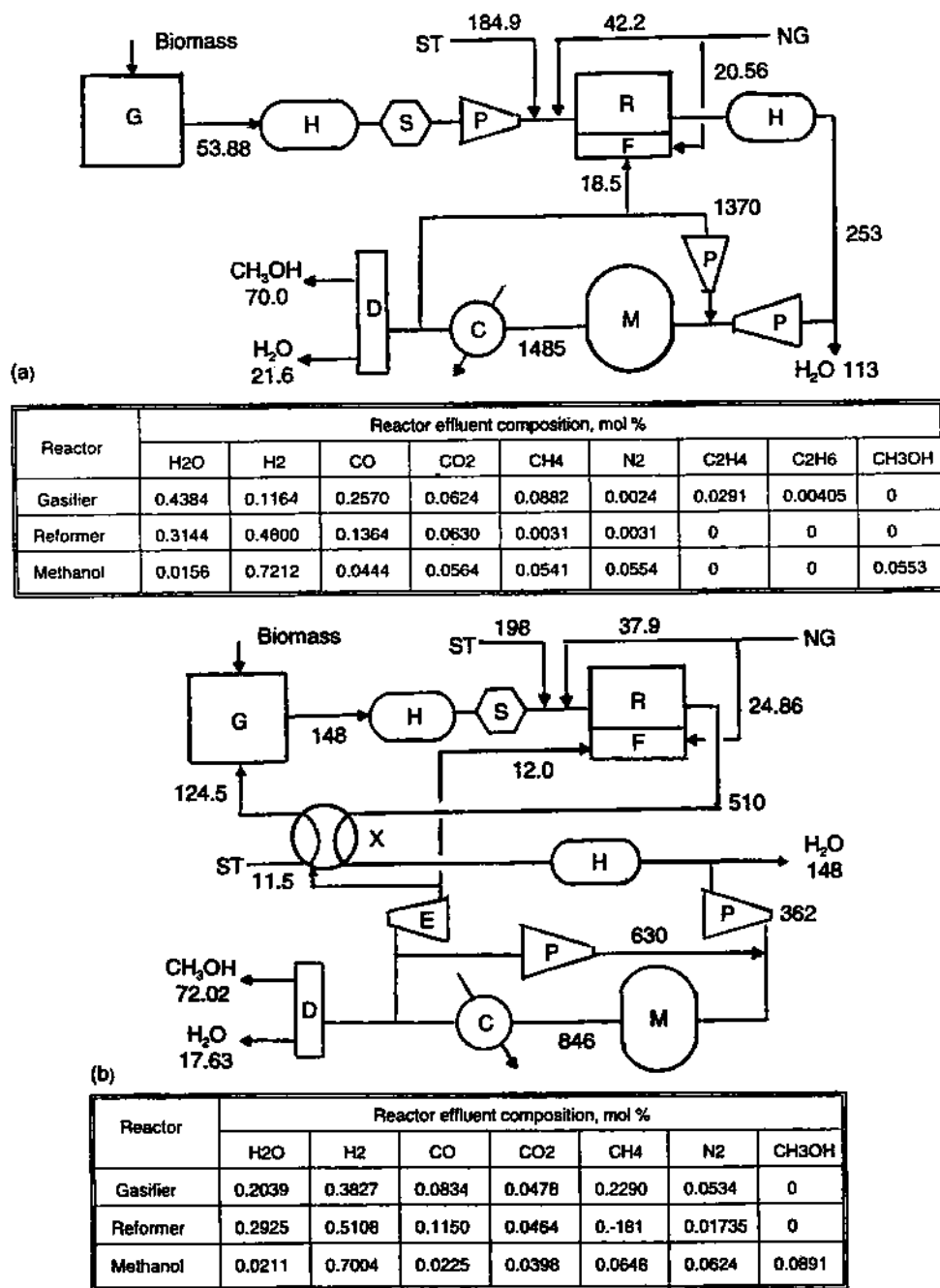
| Reactor | Reactor effluent composition, mol % | | | | | | | | |
|---------|------|------|------|------|------|------|------|------|------|
|         | H2O  | H2   | CO   | CO2  | CH4  | N2   | C2H4 | C2H6 | CH3OH |
| Gasifier | 0.4384 | 0.1164 | 0.2570 | 0.0624 | 0.0882 | 0.0024 | 0.0291 | 0.00405 | 0 |
| Reformer | 0.3144 | 0.4600 | 0.1364 | 0.0630 | 0.0031 | 0.0031 | 0 | 0 | 0 |
| Methanol | 0.0156 | 0.7212 | 0.0444 | 0.0564 | 0.0541 | 0.0554 | 0 | 0 | 0.0553 |

| Reactor | Reactor effluent composition, mol % | | | | | | |
|---------|------|------|------|------|------|------|------|
|         | H2O  | H2   | CO   | CO2  | CH4  | N2   | CH3OH |
| Gasifier | 0.2039 | 0.3827 | 0.0834 | 0.0478 | 0.2290 | 0.0534 | 0 |
| Reformer | 0.2925 | 0.5108 | 0.1150 | 0.0464 | 0.-181 | 0.01735 | 0 |
| Methanol | 0.0211 | 0.7004 | 0.0225 | 0.0398 | 0.0648 | 0.0624 | 0.0891 |

**Figure 1.** Simplified process flow diagram for (a) modified BCL process and (b) Hynol process. Numbers are streamflows in moles per metric ton of dry biomass feed. Symbols denote gasifier (G), heat recovery steam generator (H), desulfurization and cleanup units (S), compressor (P), reformer (R), furnace (F), methanol converter (M), condenser (C), distillation unit (D), expander (E), and ceramic heat exchanger (X). Biomass moisture 10 wt %.

−10K approach during reforming, +12K for methanol synthesis, and 87% gasification of the biomass carbon. Operating pressures were optimized independently for each system. Pressure drops in heat exchangers are allocated on the basis of area: the reformer pressure drop is taken to be 2.3 atm, and the methanol converter, 0.5 atm. Because $CO_2$ emission is a primary basis for these comparisons, each process was configured to generate all electric power required by that process. They are thus independent of import or export of electric power and the emissions of $CO_2$ that would otherwise be associated with the generation or displacement of that power. Electric power plants are large stationary sources of $CO_2$ emissions comparable in magnitude to transportation. If greenhouse gas mitigation is to be considered, one must ask which of these sources could

be reduced in the most cost-effective manner. The results of these simulations were therefore used to compare the cost and effectiveness of these process options for reducing $CO_2$ emissions from mobile sources and compare that strategy with published estimates for the stationary source option.

**Results**

Figure 1 is a simplified block flow diagram of the two conceptual process options examined here to utilize both NG and biomass as feedstocks. The modified BCL process, Figure 1a, utilizes a biomass gasifier developed by BCL[15] to which additional units were added for methanol production as described by Katofsky.[10] Although the BCL gasifier is assumed here, the process

could utilize a gasifier heated by an internal heat exchanger/combustor[16] or any gasifier system that would incorporate an air separation unit, at additional cost, to supply $O_2$ for in situ partial oxidation of biomass. The BCL gasifier employs an external combustor, fired with ungasified char and biomass, to provide the energy for biomass gasification. Both the gasifier and combustor operate at atmospheric pressure. The gases produced are cleaned, compressed to 14 atm, and catalytically reformed at 950 °C after addition of 185 mol of superheated steam and 42.2 mol of NG/metric ton of biomass gasified. An additional 20.56 mol of NG is used as reformer fuel, supplemented by 18.5 mol of purge gas leaving the methanol converter.

Unlike the original BCL process, no shift reactor or $CO_2$ removal unit is required to prepare the synthesis gas for the methanol converter. The syngas is compressed to 50.5 atm, and methanol is synthesized at 260 °C and 50 atm pressure. Steam is recovered from the methanol reactor at 250 °C and 39 atm for use as process steam and electric power generation. The crude methanol contains 70.0 mol of $CH_3OH$ and 21.6 mol of $H_2O$, which are separated by distillation. A series of heat exchangers following the reformer generates the steam needed for reforming, heats the boiler feedwater for the methanol steam generator, and generates low-pressure steam for the biomass drier and gasifier. No electric power import is needed: in addition to power generated by steam from the high-temperature gases leaving the reformer, power is generated from steam generated from energy recovered from the hot flue gas leaving the reformer furnace (in addition to that required for preheating the furnace air and the reformer feed stream). This energy balance on the system, including electric power for compression, fans, and pumps, determines the amount of purge gas and NG required for reformer fuel and thus affects the methanol yield. Thermal efficiency is 66.6%, defined as

$$\text{thermal efficiency} = \frac{(\text{mol of MeOH produced})\text{HHV}_{\text{MeOH}}}{\text{HHV of NG plus biomass feedstocks}}$$

where HHV of NG = $[\text{HHV}_{CH_4}(NG_p + NG_f)\%CH_4]$ + $[\text{HHV}_{C_2H_6}(NG_p + NG_f)\%C_2H_6]$ and $NG_p$ = moles of natural gas used as process feedstock; $NG_f$ = moles of natural gas used as reformer fuel; $\text{HHV}_{\text{MeOH},CH_4,C_2H_6}$ = higher heating value of methanol, methane, and ethane, in kilocalories per mole; and HHV of dry biomass = 4604 kcal/kg.

Figure 1b shows the Hynol process,[17,18] the unique features of which are (i) a hydrogasifier[19] that does not require external heating, (ii) a high-temperature heat exchanger following the reforming step that recovers heat and returns it to the gasifier, and (iii) a recycle stream (primarily $H_2$) returned from the methanol synthesis reactor to the gasifier. The recycle stream entering the gasifier at 900 °C has sufficient enthalpy to gasify the biomass without external heating, or the internal partial oxidation of biomass, that is required by other gasifier types. Steam added to the recycle stream eliminates equilibrium limitations on gasifier carbon conversion, which is thus a function only of mass transfer and reaction kinetics.

The Hynol gasifier operates at 800 °C and 41 atm. The gasification products are desulfurized by ZnO at 268 °C prior to reforming at 950 °C with a steam/carbon

ratio of 2.5, and methanol synthesis at 90 atm pressure. Assuming the same 87% carbon conversion as the BCL gasifier, an optimized Hynol system[13] would obtain a methanol yield of 72.02 mol/metric ton of biomass fed with the same amount of total NG used in the modified BCL system. In this case, 37.9 mol of NG is fed to the process and 24.9 mol of NG as reformer fuel. Because Hynol is a closed system, all of the carbon of the gasified biomass and NG added to the process can be converted to methanol except for a small amount that must be purged to control inert nitrogen accumulation that enters the system with the biomass and NG. That purge stream, 12 mol, is fed to the reformer as fuel. Unconverted biomass char is used in a separate combustor to preheat the reformer air. The amount of NG required for reformer fuel is determined mainly by the process steam requirements, including that needed for biomass drying and for generating the electric power to operate all compressors, pumps, and fans. The overall energy balance yields a thermal efficiency of 68.3%.

## Discussion

A methanol yield of 0.782 mol could be obtained from 1 mol of NG by the conventional steam reforming process. The BCL process, using biomass alone, could produce 1.477 mol of methanol from 100 kg of biomass. By comparison, the process simulations shown above indicate that a combined system using both NG and biomass can improve the methanol yield from the same amount of feedstocks by 10–13%. The improvement can be explained as follows: (i) The ratio of H/C in biomass is too low to produce methanol without consuming part of the gasified carbon to react with steam (by water–gas shift reaction) to produce the extra hydrogen needed and the resulting $CO_2$ is lost. By adding NG, the gas leaving the reformer has the proper $H_2$/CO ratio for methanol synthesis; no shift reaction is required, and all carbon goes into the methanol. (ii) When NG alone is used to make methanol by the conventional route, excess $H_2$ is produced beyond that required for methanol synthesis and can only be used as reformer fuel. (iii) In the Hynol system, hydrogen is returned to the gasifier where it reacts exothermally with biomass to provide part of the necessary gasification energy—which, in other gasifier types, is produced by partial oxidation of biomass within the gasifier or in an external combustor such as the BCL system. For this reason, Hynol is slightly more efficient than the modified BLC process.

Any alternative fuel that might significantly displace petroleum or reduce greenhouse gas emissions must be producible in amounts that are meaningful in relation to the 19 EJ of energy consumed annually by road transport in the U.S. Few alternative energy sources can meet that requirement, even with the leveraging of fuel efficiency provided by FCVs. When reduction of $CO_2$ emissions is also an objective, the options are further limited. These considerations favor methanol, which is an efficient hydrogen source for FCVs and capable of additional leveraging of $CO_2$ mitigation by use of renewable biomass as cofeedstock with natural gas. The 5.8 EJ of biomass energy that could be produced sustainably in the U.S., on land suitable for that purpose, would yield about 3.2 EJ of methanol by, for example, the BCL process if not supplemented by a cofeedstock. The modified BCL process, on the other hand, could produce 15.1 EJ of methanol. This leverag-

ing of petroleum displacement by a factor of 4.75 will be leveraged again by a factor of as much as 2.5 when the methanol is used in FCVs. The above options for methanol production will be examined here for their potential to reduce $CO_2$ emissions and their cost relative to gasoline.

**Fuel-Cycle $CO_2$ Emission.** The production of biomass involves emissions from fertilizer manufacture, $N_2O$ and $NO_x$ emissions from fertilizer use, and emissions from diesel fuel used in planting, harvesting, and transporting biomass. Natural gas production involves the release of $CO_2$ extracted from the well with the natural gas—which may, or may not, be removed as an impurity—methane leakage during extraction and transport, fuels used in drilling and operation of NG wells, fuels used in purification of the natural gas, and energy needed for pipeline transport. Because some of these greenhouse gas emissions are not $CO_2$, they must be accounted for according to their $CO_2$ equivalents; De-Luchi[20] has evaluated the process energy consumed and equivalent emissions for each stage of the fuel cycle for production of gasoline, natural gas, and biomass. Using those emission factors and a basis of 1 metric ton of biomass, the following $CO_2$-equivalent emissions and net emission reductions were calculated:

| | equiv of $CO_2$ emission, kg |
|---|---|
| biomass production (1000 kg) | 155 |
| natural gas production (62.76 kg mol) | 589 |
| methanol distribution (70.0 kg mol) | 248 |
| methanol distribution (72.02 kg mol) | 255 |
| reformulated gasoline production and distribution (100 gallons) | 280 |

Emission from the combustion of 100 gal of reformulated gasoline (814 kg of $CO_2$), plus that due to its production and distribution, totals 1094 kg of $CO_2$. Assuming a FCV efficiency 2.5 times that of current gasoline vehicles, the 70 mol of methanol produced by the modified BCL process would displace 918 gal of gasoline with a net overall fuel-cycle $CO_2$ emission reduction of

$$918(1094/100) - 62.76(44) - 589 - 155 - 248 = 6289 \text{ kg}$$

And for the Hynol process, the net emission reduction would be 6572 kg of $CO_2$. The alternative use of these two resources for production of methanol independently, using biomass in the BCL process and conventional steam reforming of natural gas, would yield 14.77 mol of methanol from 1 metric ton of biomass and 49.08 mol of methanol from 62.76 mol of NG, which could displace 837 gallons of gasoline if used in FCVs. In that case, the total net $CO_2$ emission reduction would be 5425 kg. Thus, the modified BCL system would be 6289/5425 = 1.159 or 15.9% more effective in reducing greenhouse gas emissions from the FCV fleet, and the Hynol process would be 21% more effective than the alternative option of utilizing the same feedstocks for producing methanol in separate processes.

If methanol is produced from biomass alone, the only net $CO_2$ emission occurs from the use of fossil fuels for the cultivation, harvest, and transport of the biomass and for the production of any electric power imported to the process. The overall tailpipe reduction in fuel-cycle $CO_2$ emission in that case is about 85%. When methanol is produced from NG as well as biomass, the potential net $CO_2$ reduction is less because the NG

component of its carbon is not renewable. In the cases discussed in this paper, NG represents 75% of the total feedstock energy and the resulting tailpipe $CO_2$ reduction is 67%. It is not the tailpipe emissions from a single vehicle, however, that is the important parameter; it is the total emission reduction from the vehicle fleet. Because of the leveraging factor provided by NG in a combined feedstock system, the vehicle fleet to which methanol can be provided is 4.7 times larger than a fleet that could be served by fuel produced from biomass alone. Even though the tailpipe emission is lower, the larger petroleum displacement achievable in the former case results in twice as much overall net fuel-cycle $CO_2$ emission reduction from the vehicle fleet.

**Production Cost.** A carbon tax may be an economically efficient means of mitigating $CO_2$ emissions;[21] however, given a fuel-neutral policy and the absence of a carbon tax, the first test of feasibility for displacing petroleum with alternative fuels will be cost competitiveness. The cost of producing a clean transportation fuel with lower $CO_2$ emission must be balanced not only against the price of petroleum fuels but also against the cost of mitigation from electric utilities, the other, roughly equal $CO_2$ source. Preliminary cost estimates of the two processes utilizing both biomass and NG for methanol production are discussed here and then compared with the cost of $CO_2$ mitigation from power plants.

In accordance with Marrison and Larson,[11] the delivered price of biomass produced on dedicated energy plantations in the north central region of the U.S. was taken to be $61/dry metric ton. Equipment costs are based on data of Williams et al.,[22] who evaluated the BCL process at a plant size of 1650 metric tons/day. The costs of those components were scaled up to 7870 metric tons/day using a scaling exponent of 0.70 for all plant facilities except the methanol converter, which used an exponent of 0.66. The Hynol gasifier cost is based on the Fluor/EPRI estimate for the Texaco gasifier,[23] resized on the basis of relative gas throughputs and indexed to 1994 dollars. Projected production costs are based on a discounted cash flow rate-of-return of 10% after taxes and after adjusting for inflation. Other economic factors include 15-yr depreciation with constant annual expenses; capital recovery of 15.45%; and 26% corporate income tax rate.

Table 1 shows the estimated cost of methanol production for the modified BCL and Hynol processes. The total capital investment is taken as 125% of the total cost of the itemized equipment that comprise the plant facilities. The operating cost and production cost assume 329 days of total operation per year. With NG priced at $2.37/GJ HHV, the estimates show production costs of $6.29/GJ LHV (38 cents/gal) for the modified BCL process and $6.89/GJ LHV (42 cents/gal) for Hynol.

Figure 2 compares methanol and gasoline costs as a function of the price of NG and crude oil. The basis is fuel production cost only, which avoids uncertainties about future tax policies for alternative fuels. It also excludes the external costs of end use, which would greatly reduce the relative costs of methanol.

**$CO_2$ Mitigation Cost.** The cost of gasoline should be compared with that of alternative fuels on the basis of gasoline that is reformulated to approach the lower emission levels of alternative fuels used in IC engines. Reformulation involves the reduction of Reid vapor pressure, benzene, and aromatics and the addition of

**Table 1. Investment, Operating, and Methanol Production Cost Estimates for the Hynol and Modified BCL Processes[a]**

| | cost, $ million | |
|---|---|---|
| component | hynol process | mod. BCL process |
| Plant Facilities Investment | | |
| feed preparation | 39.3 | 39.3 |
| gasifier | 292.5 | 38.0 |
| ceramic heat exchanger | 97.5 | 0 |
| gasifier loop compressor | 114.5 | 35.5 |
| reformer | 173.2 | 139.1 |
| methanol synthesis | 242.5 | 356.0 |
| utilities and auxilliaries | 81.4 | 81.4 |
| total plant facilities investment | 1041 | 689 |
| total capital investment | 1301 | 862 |
| Operating Cost per Day | | |
| biomass | 0.4801 | 0.4801 |
| natural gas | 0.9752 | 0.9752 |
| operation and maintenance | 0.1901 | 0.1259 |
| catalysts | 0.00102 | 0.0667 |
| purchased energy | 0 | 0 |
| capital charge | 0.2376 | 0.1574 |
| total operating cost | 1.884 | 1.805 |
| methanol production cost, $/GJ | 6.09 | 5.56 |

[a] Basis: 7870 metric tons/day (biomass) plant, biomass delivered @ $61/metric tons, NG @ $2.37/GJ ($2.50/10^6 Btu, HHV).
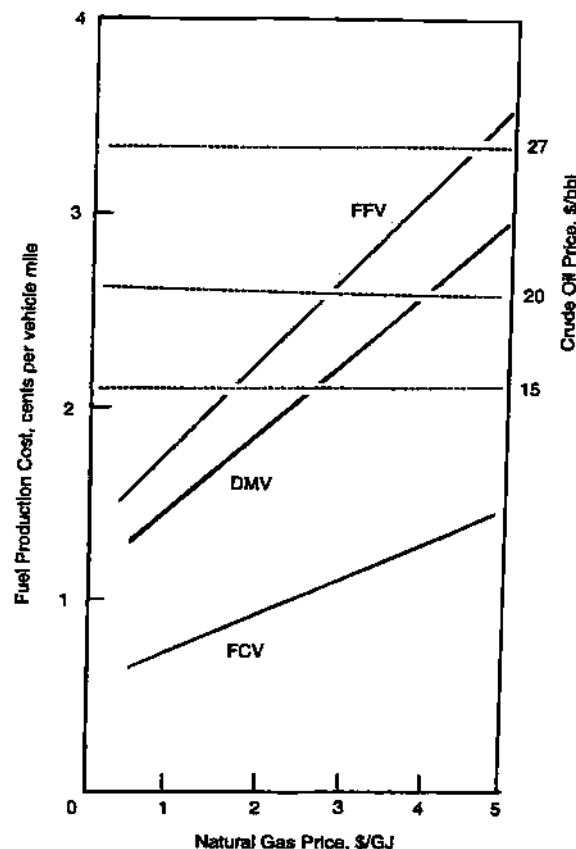


**Figure 2.** Comparison of fuel production costs with reformulated gasoline. Basis: gasoline fuel economy = 27 miles/gallon used in an internal combustion engine vehicle (ICEV). FFV = M85 in flexible fuel ICEV; DMV = M100 in dedicated ICEV; FCV = methanol in fuel-cell vehicle. Methanol produced by modified BCL process. Dashed lines denote gasoline produced at indicated crude oil price and used in ICEVs.

oxygenates. Reformulated, low-sulfur gasoline with an energy content of 40.75 MJ/kg LHV has a production cost of about 70 cents/gallon, or $5.8/GJ LHV.

**Table 2. Total Fuel-Cycle $CO_2$ Emission Reduction by Methanol Produced from Biomass and Natural Gas Relative to Emission from ICEVs Using Reformulated Gasoline[a]**

| | hynol process | | | modified BCL process | | |
|---|---|---|---|---|---|---|
| | vehicle fleet $CO_2$ emission avoided | | cost per metric ton of $CO_2$, $ | vehicle fleet $CO_2$ emission avoided | | cost per metric ton of $CO_2$, $ |
| vehicle type | % | metric tons | | % | metric tons | |
| FFV[b] | 9.4 | 0.557 | +45 | 7.7 | 0.439 | −11 |
| DMV[c] | 36 | 2.08 | −25.1 | 34 | 1.92 | −42 |
| FCV[d] | 67 | 7.74 | −53.4 | 66 | 7.41 | −57 |

[a] Basis: One metric ton biomass and 6.276 mol of NG. [b] Flexible fuel vehicle using M85 (85% methanol, 15% regular gasoline). [c] Dedicated methanol vehicle using M100 (neat methanol). [d] Fuel cell vehicle using neat methanol.

One gallon of methanol, produced at a cost of 42 cents/gal and used in a dedicated IC-engine vehicle, would displace 0.698 gallon of gasoline (relative efficiency = 1.27, volumetric energy ratio = 0.549, LHV) in which case the fuel-cycle $CO_2$ emission reduction would be 3.90 kg/gallon of gasoline displaced. The cost of displacing 1 gallon of gasoline would be 42/69.8 = 60.2 cents and the cost per metric ton of $CO_2$ emission avoided is

$$\frac{\$0.602 - \$.070}{3.90}(1000) = -\$25.2/\text{metric ton of } CO_2$$

Flexible fuel ICEVs, currently in production, using M85 (85% methanol, 15% regular gasoline) will require 1.67 gallons of M85 to displace 1 gallon of gasoline (relative efficiency 1.05, volumetric energy ratio = 0.570). The production cost of M85 on that basis is $0.447/gal; it therefore takes 74.7 cents worth of M85 to displace 1 gallon of reformulated gasoline valued at 70 cents, and the cost per ton of $CO_2$ emission avoided is $45 relative to reformulated gasoline used in ICEVs. Similar calculation for M85 produced by the modified BCL process gives a cost per metric ton of $CO_2$ emission avoided at minus $11.3 when used in flexible fuel vehicles.

When used in FCVs having a relative efficiency of 2.5, 1 gallon of Hynol methanol valued at 42 cents would displace 1.37 gallons of reformulated gasoline valued at 96 cents that would have been used in conventional vehicles, and a net reduction of 7.37 kg of fuel-cycle $CO_2$ emissions would be obtained per gallon of gasoline displaced. In this case, the cost of $CO_2$ mitigation is minus $53/metric ton of $CO_2$ emission avoided. Table 2 summarizes the effectiveness and cost of $CO_2$ mitigation from vehicles using methanol produced from natural gas and biomass relative to current vehicle technology using reformulated gasoline. The following results are noted: (i) the net overall $CO_2$-equivalent fuel cycle emission from the vehicle fleet is reduced for all types of vehicles relative to the current vehicle/fuel system, (ii) the cost of methanol will be significantly less than the cost of the gasoline it displaces in all cases but one, and (iii) about 66% fuel-cycle $CO_2$ emission reduction would be possible in FCVs at a cost saving of over $50/metric ton of $CO_2$ emissions avoided.

FCVs incorporating partial oxidation reformers that can use gasoline are also under development, and the initial commercialization of FCVs in the U.S. will probably use gasoline, especially during the period of transition from conventional IC to FC vehicles. The relative impacts of gasoline and methanol FCVs on the sustainability issues need to be examined even though the performance of neither system has been well estab-

lished. A preliminary estimate of the efficiency of the gasoline–FCV system[24] is 75–83% for conversion of gasoline to hydrogen by the fuel processor and 45–50% for the fuel cell, or about 40% efficiency in converting the LHV of gasoline to electric power; adding the power losses of the electric motor and power train, the overall efficiencies of the methanol and gasoline FCV would be similar. The main value of methanol in this case is the potential for further reduction of $CO_2$ emission, oil dependence, and cost when externalities are included.

**Comparison with Stationary-Source $CO_2$ Mitigation.** Considerable R&D is underway to assess the feasibility and cost of $CO_2$ mitigation from coal-burning power plants.[25,26] Those technologies involve recovery of $CO_2$ from combustion gases, usually by amine scrubbing, and sequestration in the ocean or underground repositories. Feasibility has been established for a number of technologies, and preliminary costs have been estimated. Application to a U.S. power plant was examined in detail[27] for recovery of 65% of the $CO_2$ from an oxygen-blown, coal gasification combined-cycle power plant having a net output of 411 MW for the complete energy cycle. The total net cost of $CO_2$ recovery, purchased makeup power, transporting 255 metric tons/h recovered $CO_2$ by a 500-mile pipeline, and its sequestration in depleted oil or gas wells is $72.7/metric ton of $CO_2$ emission avoided.

Clearly, mitigation of greenhouse gas emissions from mobile sources would be more cost-effective than from stationary sources, the difference amounting to nearly $126/metric ton of $CO_2$ emission avoided. In addition to the cost differential of $CO_2$ mitigation represented by this comparison, the displacement of imported oil used for transportation has economic and environmental benefits which justify that displacement independently of the climate change issue—benefits that would not accrue from abatement of emissions from power plants fueled with domestic coal.

**Reduction of Other Pollutant Emissions by Methanol.** In addition to their major contribution to $CO_2$ emissions, motor vehicles are currently responsible for 80% of the total U.S. emissions of CO and 45% of the $NO_x$ and VOC. A dedicated methanol ICEV would produce much lower evaporative emissions than a vehicle using reformulated gasoline and equal or lower exhaust emissions of the criteria pollutants, plus substantial reduction of 1,3-butadiene and benzene emissions.[28] A methanol FCV is expected to emit 99% less CO, 83% less $NO_x$, and 87% less VOC than conventional vehicles and eliminate essentially all particulate emissions. The economic benefits of reducing the external costs of air pollution impacts of petroleum fuels also need to be taken into account when alternative fuels are compared with petroleum. This is particularly important when the national interest in development of fuel technology and the sustainability of alternative fuel options is assessed. Although the cost benefit of $CO_2$ emission reduction can be compared only with the other option of stationary source mitigation, the external costs of air pollution impacts are known to add significantly to the real cost of petroleum fuels.[8] Those costs include the effects of air pollution on health and dependence on foreign petroleum sources which add at least 31 cents/gal, and possibly more than $3/gal, to the real cost of gasoline.

**Conclusions**

The cost of alternative fuels should be assessed on the basis of the production cost of reformulated gasoline, to partially account for the value of reduced emissions of criteria pollutants. The comparison must also account for the end-use efficiency of current and emerging vehicle technologies, especially fuel cells. From the standpoint of national interests, the external costs of petroleum fuels should also be taken into account in evaluating alternative fuels.

From the standpoint of sustainability, the effectiveness of fuel/vehicle system options on reducing greenhouse emissions must also be considered and the cost-effectiveness of mitigation options in the transportation sector compared with mitigation of stationary sources. The two alternative fuel processes examined here could produce methanol at a projected cost that would be less than the equivalent cost of the gasoline they replace. When used in flexible fuel vehicles and dedicated methanol vehicles during a transition period to fuel cell vehicles, net fuel-cycle $CO_2$ emission reductions of 7.7–34% could be obtained at no cost relative to current vehicle/fuel systems. In fuel cell vehicles, a 66% reduction of $CO_2$ emissions from the vehicle fleet would be expected, together with near elimination of criteria pollutant emissions at half the current fuel cost per vehicle mile traveled.

Mitigation of $CO_2$ emissions from mobile sources would be more cost-effective than mitigation from stationary sources.

Production of methanol from biomass as a means of reducing greenhouse gas emissions from road transport will be more effective if natural gas is used as cofeedstock in a single process. A 15.9–21% greater overall $CO_2$ emission reduction would be obtained relative to use of the same resources in separate processes. The amount of petroleum that could be displaced by biomass produced sustainably in the U.S. would be increased by a factor of 4.7 compared to the displacement that could be obtained if biomass alone were converted to alcohol fuel and twice as much net overall fuel-cycle $CO_2$ emissions reduction would be achieved.

**Nomenclature**

BCL = Battelle–Columbus Laboratory
bbl = barrel (42 gallons)
FCV = fuel cell vehicle
GJ = $10^9$ joules
HHV = higher heating value
IC = internal combustion
ICEV = internal-combustion-engine vehicle
LHV = lower heating value
MJ = $10^6$ joules
NG = natural gas
ST = steam
VOC = volatile organic compounds

**Literature Cited**

(1) Reducing Risk: Setting Priorities and Strategies for Environmental Protection. U.S. Environmental Protection Agency, Science Advisory Board, SAB-EC-90-021, Washington, DC, 1990.

(2) Gordon, D. Sustainable Transportation: What Do We Mean and How Do We Get There? In *Transportation and Energy: Strategies for a Sustainable Transportation System*; Sperling, D., Shaheen, S. A., Eds.; American Council for an Energy-Efficient Economy: Berkeley, CA, 1995.

(3) Energy and Transportation. President's Council on Sustainable Development, Task force report, Washington, DC, 1997.

(4) Transportation Science and Technology Strategy. National Science and Technology Council, Committee on Transportation Research and Development, Washington, DC, 1997.

(5) Developing a Research Agenda for Sustainable Transportation. Energy Foundation, Surface Transportation Policy Project, Washington, DC, 1997.

(6) Toward a Sustainable Future: Addressing the Long-Term Effects of Motor Vehicle Transporation on Climate and Ecology. National Research Council; Committee for the Study of Transportation and Sustainable Environment, Washington, DC, 1997.

(7) Lange, J. P. Perspective for Manufacturing Methanol at Fuel Value. *Ind. Eng. Chem. Res.* **1997**, *36*, 4282–90.

(8) DeLuchi, M. A. The Annualized Social Cost of Motor-Vehicle Use in the U.S., 1990–1991: Summary of Theory, Data, Methods, and Results. UCD-ITS–RR-96-3, Institute of Transportation Studies, University of California, Davis, CA, 1997.

(9) Analysis of the Economic and Environmental Effects of Methanol as an Automotive Fuel. U.S. Environmental Protection Agency; report 0730 (NTIS PB90-225806), Office of Mobile Sources, Ann Arbor, MI, 1989.

(10) Katofsky, R. E. The Production of Fluid Fuels from Biomass. Center for Energy and Environmental Studies, PU/CEES 279, Princeton University, Princeton, NJ, 1993.

(11) Marrison, C. I.; Larson, E. D. Cost Versus Scale for Advanced Plantation-Based Biomass Energy Systems in the U.S.A. and Brazil. *Proceedings of the Second Biomass Conference of the Americas*; NREL/CP-200-8098; National Renewable Energy Laboratory, Golden, CO, 1995; pp 1272–1290.

(12) Sweeney, J. L. Costs of Producing Alternative Fuels. In *Methanol As An Alternative Fuel Choice: An Assessment*; Kohl, W. L., Ed.; International Energy Program, Johns Hopkins University, Washington, DC, 1990.

(13) Borgwardt, R. H. Hynol Process Evaluation. EPA-600/R-97–153 (NTIS PB98–127319), U.S. Environmental Protection Agency, Research Triangle Park, NC, 1997.

(14) California Fuel Methanol Cost Study. Bechtel, Inc.: San Francisco, CA, 1988; Vol. 2, p 5–2.

(15) Feldman, H. F.; Paisley, M. A.; Appelbaum, H. R.; Taylor, D. R. Conversion of Forest Residues to Methane-Rich Gas in a High-Transport Gasifier. PNL-6570; U.S. Department of Energy, Pacific Northwest Laboratory, 1988.

(16) Schiefelbein, G. F. Testing of an Advanced Thermochemical Conversion Reactor System. PNL-7245, U.S. Department of Energy, Pacific Northwest Laboratory, 1990.

(17) Steinberg, M.; Dong, Y. Process and Apparatus for the Production of Methanol from Condensed Carbonaceous Material. U.S. Patent 5,344,848, 1994.

(18) Steinberg, M.; Dong, Y. Hynol—An Economical Process for Methanol Production from Biomass and Natural Gas with Reduced $CO_2$ Emissions. *Proceedings, 10th World Hydrogen Energy Conference*; Pergamon: New York, 1994; Vol. 1, pp 495–504.

(19) Garg, M.; Piskorz, J.; Scott, D.; Radlein, D. The Hydrogasification of Wood. *Ind. Eng. Chem. Res.* **1988**, *27*, 256–264.

(20) DeLuchi, M. A. Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity; Center for Transportation Research. Argonne National Laboratory: Argonne, IL, 1993; ANL/ESD/TM-22, Vol. 1, p 21.

(21) Schneider, S. H.; Goulder. L. H. Achieving Low-Cost Emission Targets. *Nature* **1997**, *389*, 13–14.

(22) Williams, R. H.; Larson, E. D.; Katofsky, R. E.; Chen, J. Methanol and Hydrogen from Biomass for Transportation. Presented at Biomass Resources: A Means to Sustainable Development, Bangalore, India, 1994.

(23) Buckingham, P. A.; Cobb, D. D.; Leavitt, A. A.; Snyder, W. G. Coal-to-Methanol: An Engineering Evaluation of Texaco Gasification and ICI Methanol-Synthesis Route. AP-1962. Electric Power Research Institute: Palo Alto, CA, 1981.

(24) Espino, R. L.; Robbins, J. L. Fuel and Fuel Reforming Options for Fuel Cell Vehicles. 30th International Symposium on Automotive Technology & Automation, Florence, Italy, 1997.

(25) Block, K.; Turkenburg, W. C.; Hendricks, C. A.; Steinberg, M. *Proceedings of the First International Conference on Carbon Dioxide Removal*; Pergamon: New York, 1992.

(26) Herzog, H. J. *Proceedings of the Third International Conference on Carbon Dioxide Removal*; Pergamon: New York, 1997.

(27) Doctor, R. D.; Molburg, J. C.; Thimmapuram, P. R. *KRW Oxygen-Blown Gasification Combined Cycle: Carbon Dioxide Recovery, Transport, and Disposal*. ANL/ESD-34; Argonne National Laboratory: Argonne, IL, 1996.

(28) Wang, M. Q. Emission Reduction of Alternative-Fuel Vehicles. In *Transportation and Energy: Strategies for a Sustainable Transportation System*; Sperling, D., Shaheen, S. A., Eds.; American Council for an Energy-Efficient Economy: Berkeley, CA, 1995; p 123.