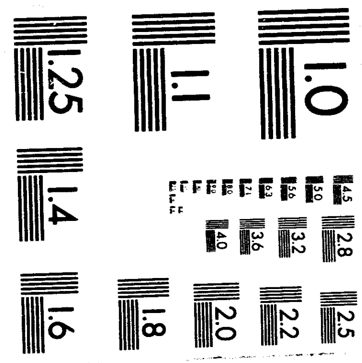
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Energy and Crude Oil Input Requirements for the Production of Reformulated Gasolines

by M. Singh and B. McNutt*

Center for Transportation Research, Energy Systems Division,
Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439

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*McNutt is affiliated with the U.S. Department of Energy.

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NOTATION

Initialisms

ANL	Argonne National Laboratory
CAAA	Clean Air Act Amendments of 1990
CG	conventional gasoline
CO	carbon monoxide
EPA	U.S. Environmental Protection Agency
EPACT	Energy Policy Act of 1992
ETBE	ethyl tertiary butyl ether
ETOH	ethanol
HC	hydrocarbon
LP	linear programming
MTBE	methyl tertiary butyl ether
NGL	natural gas liquid
NPC	National Petroleum Council
NPRM	Notice of Proposed Rulemaking
OG	oxygenated gasoline
PADD	Petroleum Administration Defense District
RIA	Regulatory Impact Analysis
RFG	reformulated gasoline
RVP	Reid vapor pressure
T.A.P.	toxic air pollutants
TM	Turner, Mason, and Company
VMT	vehicle miles traveled
VOC	volatile organic compound

Units of Measure

Btu	British thermal unit
psi	pound per square inch

ENERGY AND CRUDE OIL INPUT REQUIREMENTS FOR THE PRODUCTION OF REFORMULATED GASOLINES

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M. Singh and B. McNutt

ABSTRACT

The energy and crude oil requirements for the production of reformulated gasoline (RFG) are estimated. The scope of the study includes both the energy and crude oil embodied in the final product and the process energy required to manufacture the RFG and its components. The effects on energy and crude oil use of employing various oxygenates to meet the minimum oxygen-content level required by the Clean Air Act Amendments are evaluated. The analysis shows that production of RFG requires more total energy, but uses less crude oil, than that of conventional gasoline. The energy and crude oil use requirements of the different RFGs vary considerably. For the same emissions performance level, RFG with ethanol requires substantially more total energy and crude oil than does RFG with methyl tertiary butyl ether (MTBE) or ethyl tertiary butyl ether. A specific proposal by the U.S. Environmental Protection Agency, designed to allow the use of ethanol in RFG, would increase the total energy required to produce RFG by 2% and the total crude oil required by 2.0 to 2.5% over the corresponding values for the base RFG with MTBE.

1 INTRODUCTION

The Clean Air Act Amendments (CAAA) of 1990 require that, beginning in 1995, reformulated gasoline (RFG) replace conventional gasoline in the nine worst ozone nonattainment areas in the United States with a 1980 population of 250,000 or more (Section 211(k)). Other ozone nonattainment areas may also require the use of RFG as an element of their states' State Implementation Plans. The CAAA establish general requirements to be met by RFG (nitrogen oxide emissions and oxygen, benzene, and heavy metals content), and they also require that RFG meet the more stringent of either a formula or a performance standard for volatile organic compounds (VOCs) and toxic air pollutants. The performance standards are more stringent for 2000 than for 1995. The U.S. Environmental Protection Agency (EPA) is responsible for promulgating the regulations implementing the RFG program.

The CAAA state that in developing the RFG regulations, the EPA should require the greatest reductions achievable in ozone-forming VOCs and toxic air-pollutant emissions, taking into consideration the cost of achieving the emission reductions, any nonair-quality- and other air-quality-related health and environmental impacts, and *energy requirements* (Section 211(k)(1)). This report provides an analysis of the energy and crude oil input requirements associated with the production of various RFGs that would meet the EPA RFG program requirements. Differences in energy and crude oil use among RFGs meeting the same performance standards exist for a number of reasons. In particular, the oxygenates used to provide the required oxygen content for RFG vary in volume, energy content, volatility, and energy required to produce them. The oxygenates, in turn, affect the volume and composition of the hydrocarbon (HC) portion of the RFG.

The specific stimulus for the analysis presented in this report is the February 1993 EPA Notice of Proposed Rulemaking (NPRM) on RFG, which would allow RFG blended with ethanol to meet a lesser VOCs reduction standard (Phases I and II) or a lesser Reid vapor pressure (RVP) standard (Phase I) than RFGs produced with other oxygenates (FR Vol. 58, No. 37). (Phase I RFG is required from 1995 through 1999, and Phase II RFG is required beginning in 2000.) The EPA appears to have considered energy requirements as a basis for this proposal. The preamble of the EPA NPRM makes reference to the possibility of energy or oil savings and associated energy security benefits with implementation of the proposal. However, neither the NPRM nor the Draft Regulatory Impact Analysis (RIA) (February 5, 1993) presents any data or analysis to document such benefits. The analysis presented in this report assesses these presumed savings.

While the stimulus for the analysis presented here is EPA's specific proposal, the results of the analysis are applicable more generally than to the proposal alone. Alternative forms of using ethanol in RFG other than that proposed are considered in this analysis (e.g., ethanol in ethyl tertiary butyl ether [ETBE]). This report also provides estimates of energy and crude oil requirements associated with RFG with methyl tertiary butyl ether (MTBE) as oxygenate, as well as of such requirements associated with the production of conventional gasoline and gasoline oxygenated for use in programs aimed at controlling carbon monoxide (CO) emissions.

2 METHODOLOGY

2.1 ANALYTICAL FRAMEWORK

The overall framework for the analysis considered in this report is reflected in Figure 1. For each type of RFG, the volume and type of feedstock (e.g., hydrocarbon, alcohol, and isobutylene) required for the gasoline and oxygenate components are estimated. The process energies are also estimated, by amount and type, for refining the hydrocarbons and producing the alcohols, the isobutylene, and the ethers. Together, these process energies and feedstocks define the composite energy and oil requirements of RFG with MTBE, ethanol, and ETBE as oxygenates. The various RFGs are evaluated on the basis of their delivering equal energy for constant vehicle miles traveled (VMT).

The analysis focuses on the production of year 2000 (summer), VOC-controlled RFGs. The RFGs contain 2.1% oxygen by weight[1] and are produced in a modeled, typical Petroleum Administration Defense District (PADD) II (Chicago area) complex refinery. The Chicago area is one of the nine areas required to use RFG and is a key market for fuel ethanol sales. Although RFG production will vary among PADDs, we believe the general trend indicated in the results presented below would be the same for other PADDs.

The baseline fuel in this analysis is RFG with MTBE, the oxygenate most likely to be used in the production of RFG. This RFG produces a VOCs reduction, relative to the CAAA baseline conventional gasoline, of 27 to 41%, depending on whether the February 1993 or April 1992 version of the proposed EPA complex model is used. The EPA is developing this model for use in implementing the RFG program. The characteristics of RFG with MTBE are indicated in Table 1. The refinery-related energy and oil inputs needed to produce this gasoline were calculated by Turner, Mason, and Company (TM), by using the TM refinery linear programming (LP) model, for the National Petroleum Council (NPC) Refinery Study (1993).

The constraints on the refinery LP model were changed to reflect a mixed RFG pool, with 70% of the RFG using MTBE as the oxygenate and 30% using ethanol, both at the 2.1% oxygen content level consistent with the requirements of the February 1993 EPA NPRM. The characteristics of this mixed RFG pool are described in Table 1. The VOCs performance of the mixed RFG pool was held to the original 41% per the April 1992 version of the EPA complex model. The total energy content of the total volume of RFG produced daily (i.e., volume × specific energy content) and other key product characteristics and product volumes (e.g., diesel fuel) were held constant. The refinery model was allowed, within these constraints, to optimize on the basis of cost. Energy and crude oil input requirements were then recalculated.

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[1] The CAAA require that the oxygen content of RFG be a minimum of 2.0% by weight. The oxygen content of 2.1% used in this analysis reflects the estimated compliance margin specified in a study (the NPC Refining Study) conducted by the National Petroleum Council (1993) of the implications of the CAAA for the refinery industry.

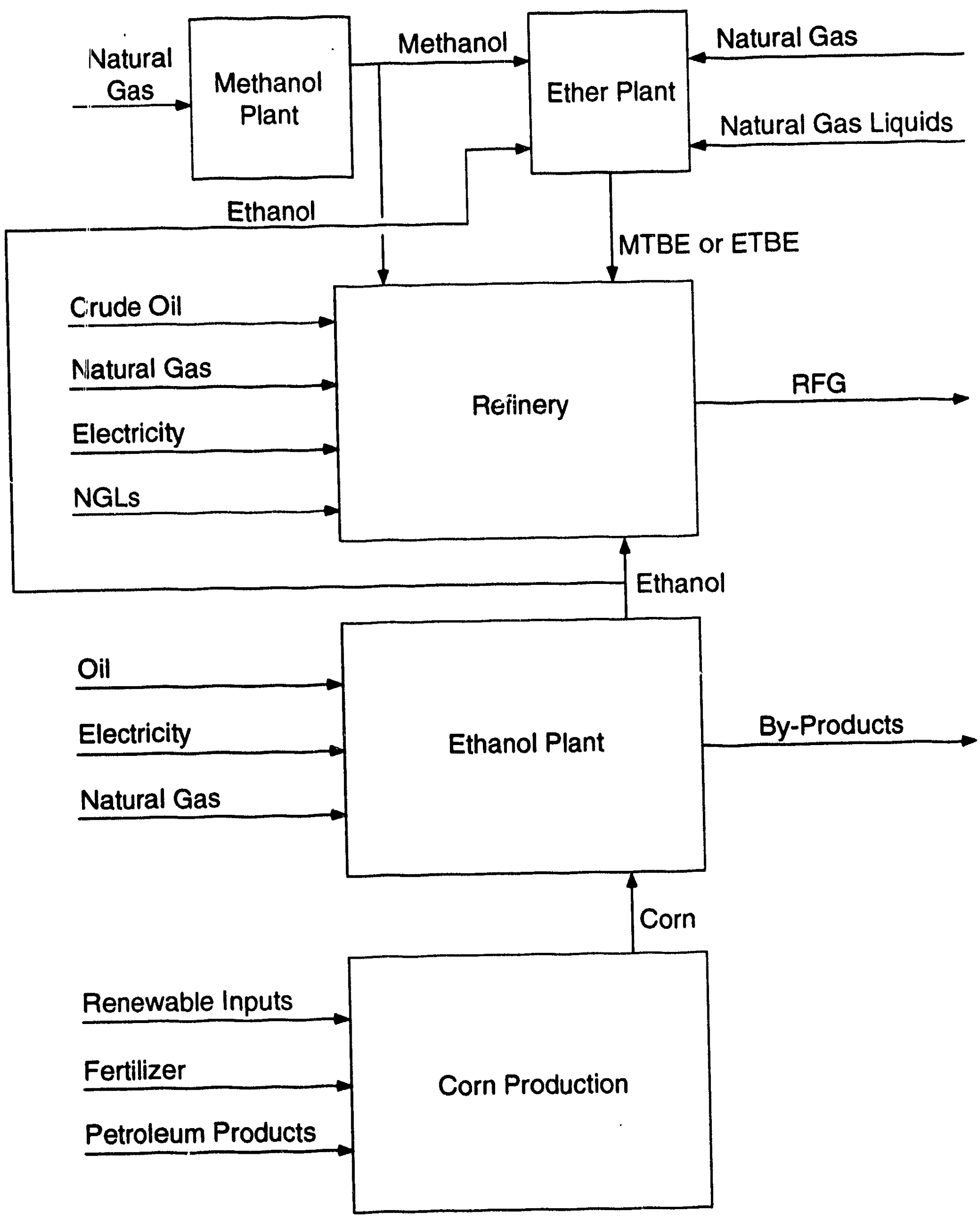

FIGURE 1 Overall Framework Employed in Analysis of Energy and Oil Requirements for RFG Production

The NPC Refining Study did not include a separate LP model run of ethanol use in the pool at the 2.7% level. The EPA proposal allows the ethanol content in the pool to be as much as 2.7% oxygen content by weight. This level of use is evaluated in this report, but only in terms of changes in the component volumes required.

Ethanol may be used in RFG in other ways than that proposed by EPA. This analysis examined two such additional uses: (1) production of all the RFG with ethanol only and (2) production of all the RFG with ETBE only. As with the other RFGs analyzed in this report, these two RFGs comply with the EPA's RFG performance standard requirements (e.g., the VOCs performance standard). The NPC Refining Study did not include separate runs for either of these RFGs. However, data from the LP model runs just presented and other available LP model runs (which evaluated the energy and oil impacts of changes in the RVP of the hydrocarbon portion of the RFG) have been used to approximate the changes in the RFG HC energy and oil input requirements for these two cases. The NPC Refining Study also provided an LP model run for conventional gasoline produced in PADD II.

Argonne National Laboratory (ANL) has developed a spreadsheet model incorporating (1) the above computations of energy and oil use in the refinery production of RFG and (2) other estimates of the energy required to produce the various oxygenates outside the refinery. The model also normalizes both sets of estimates to the delivery of equal energy content. Finally, the spreadsheet model is used to derive estimates of the energy and oil needed to produce a variety of fuels with the 2.7% oxygen content required for control of carbon monoxide (CO) emissions in various areas of the country.

2.2 KEY ASSUMPTIONS AND INPUTS

The key assumptions and inputs for this analysis include the following:

- The production of 100% RFG in the PADD II Complex Refinery Model is representative of the gasoline refining situation that would exist if the regulations were to be imposed as proposed.
- The VOCs standard for 2000 is such that the refinery must operate at the "knee" in the VOCs/cost curve, with a cost-effectiveness value of about $10,000 per (summer) ton of VOCs reduced.
- All marginal changes in isobutylene demand for ether production in merchant ether plants are derived from natural gas liquids (NGLs).
- Ethanol, methanol, and ether production are as described in the sources cited below.

TABLE 1 Characteristics of Selected RFGs

Item	RFG with MTBE (Case S6)	Combined RFG: 70% with MTBE, 30% with Ethanol (Case S13H)
Properties		
Aromatics (vol %)	23.9	23.6
Oxygen (wt %)	2.1	2.1
Olefins (vol %)	10.3	10
Benzene (vol %)	0.7	0.7
Sulfur (ppm by weight)	236	86
RVP (psi)	6.6	6.8
T50 (°F)	208	209
T90 (°F)	342	327
EVAP @ 200°F (%)	47.8	47.4
EVAP @ 300°F (%)	81.5	84.8
Emissions Reduction from Statutory Base[a] (%)		
VOCs	41	41
NO_x	0	5
T.A.P.[b]	33	39

[a] Per EPA, 4/92 CF.

[b] T.A.P. = toxic air pollutants.

Source: Turner, Mason, and Co. (Table F-1, Jan. 8, 1993, draft).

The assumption involving production of 100% RFG requires explanation. The primary reason we use 100% RFG production in this analysis is that the number of gasoline types and grades that could be handled within the refinery LP model was limited. Each of the refinery LP model runs contained a regular and premium RFG with MTBE and a regular and premium RFG with ethanol. Adding conventional gasolines to these RFGs was not possible without modifying the refinery LP model structure. However, we believe that the results obtained for 100% RFG production are representative of (though not identical to) the results that would be obtained with only substantial (50% or more) RFG production. This is true in part because of the anti-dumping provisions of the RFG regulations and because the RFGs would be produced at the minimal RVP level of 6.5 pounds per square inch (psi), as in 100% RFG production. It may also be likely that once a refinery chooses to produce a substantial volume of RFG, it will in fact choose, for economic reasons, to produce virtually 100% RFG. The results presented here are believed to be representative of individual refineries. Information from the NPC Refining Study (NPC 1993) and other sources suggests that, for many refiners, the costs of moving to 100% RFG production are small relative to the logistics and marketing benefits of such production.

3 ENERGY AND CRUDE OIL REQUIRED TO PRODUCE RFG AT 2.1% OXYGEN CONTENT

Reformulated gasoline will make use of various oxygenates (MTBE, ETBE, and ethanol), and the energy content of each oxygenate differs. Moreover, the various oxygenates replace different volumes of gasoline in achieving the same oxygen level in the RFG. As a result, the type of oxygenate used and its volumetric proportion in the RFG will affect the energy delivered for vehicle propulsion. The following analysis provides estimates of the volumes of RFG of different formulations required to deliver equal energy for propulsion, as well as the crude oil content of each fuel.

The energy required to produce the various RFGs and the crude oil required in the process also vary by RFG type. This analysis presents estimates of the energy and crude oil requirements for the production of various RFGs. Tables 2 and 3 present the conclusions of the full analysis. The following discussion walks the reader through Table 2 and discusses the assumptions and data used to derive the estimates.

3.1 VOLUME OF RFG REQUIRED TO DELIVER EQUAL ENERGY CONTENT

Five RFGs or RFG product mixes are compared in Table 2: RFG with MTBE, RFG with ETBE, RFG with ethanol, and two mixed RFG pools (containing both MTBE and ethanol) that would satisfy the recent EPA proposal that up to 30% of the RFG sold in northern nonattainment areas contain ethanol. These five RFGs are designed to satisfy year 2000 (Phase II) RFG requirements in PADD II.

Also represented are two conventional gasolines (CGs). One of these gasolines is assumed to contain no ether. The other is a conventional gasoline sold or likely to be sold in PADD II in the absence of regulations requiring RFG; it contains 2% MTBE. Each type of gasoline is listed in Column 1.

Column 2 of Table 2 lists the components of each gasoline that are of particular interest in this analysis: hydrocarbons, ethers, and ethanol. Column 3 presents the share of each of these components in a gallon of each gasoline type. This share is based on the volume of ether or ethanol required to meet the minimum 2.1% oxygen-content level required of the RFG (2.7% with ethanol is assumed in one case); the source of these volume estimates is presented in Table 4. Column 4 of Table 2 presents the total energy content of each gasoline type. The total energy content is based on the share of each component in a gallon of gasoline (Column 3) and the energy content (lower heating value) of each component, as presented in Table 4. Although the energy content of HCs used in the RFGs varies slightly from one RFG to another, as demonstrated by the refinery LP runs, we have held this energy content constant here.[2]

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[2] A sensitivity analysis was run to determine the effect of varying the HC energy content. We found the effect not to be significant with respect to the conclusions of the overall analysis reported here.

TABLE 2 Fuel Volumes and Energy Content for 2.1% RFG

Fuel Type	Compo-nents	Initial Volume (gal)	Energy Content of Initial Volume (Btu)	Revised Volume to Deliver Equal Btu as RFG with MTBE Only (gal)	Revised Energy Content of Fuel (Btu)	Oil Content of Equal-Btu RFG [Feedstock] (Btu)	Energy Required to Produce Equal-Btu RFG (Btu)	Oil Required to Produce Equal-Btu RFG (Btu)	Total Energy Required to Deliver Equal-Btu RFG (Btu)	Total Oil Required to Deliver Equal-Btu RFG (Btu)
RFG with MTBE at 2.1% O_2	HCs	0.883	101,142	0.883	101,142	101,142	15,996	9,060	117,138	110,202
	MTBE	0.117	10,912	0.117	10,912	647	2,037	0	12,949	647
	Total	1.000	112,053	1.000	112,053	101,789	18,032	9,060	130,087	110,849
RFG with ETBE at 2.1% O_2	HCs	0.867	99,272	0.866	99,175	99,175	15,469	8,667	114,643	107,842
	ETBE	0.133	12,891	0.133	12,879	665	4,203	303	17,081	969
	Total	1.000	112,163	0.999	112,053	99,840	19,671	8,970	131,725	108,811
RFG with Ethanol at 2.1% O_2	HCs	0.940	107,630	0.939	107,518	107,518	22,314	13,434	129,832	120,952
	ETOH	0.060	4,540	0.060	4,535	0	3,531	339	8,067	339
	Total	1.000	112,170	0.999	112,053	107,518	25,845	13,773	137,899	121,291
RFG Mix No. 1 (70% RFG with MTBE at 2.1% O_2; 30% RFG with ETOH at 2.1% O_2)	HCs	0.900	103,088	0.900	103,056	103,056	17,841	10,336	120,897	113,392
	MTBE	0.082	7,638	0.082	7,636	121	1,454	0	9,090	121
	ETOH	0.018	1,362	0.018	1,362	0	1,060	102	2,422	102
	Total	1.000	112,088	1.000	112,053	103,177	20,356	10,438	132,409	113,615
RFG Mix No. 2 (70% RFG with MTBE at 2.1% O_2; 30% RFG with ETOH at 2.7% O_2)	HCs	0.895	102,499	0.897	102,650	102,650	17,771	10,295	120,421	112,945
	MTBE	0.082	7,638	0.082	7,649	121	1,457	0	9,106	121
	ETOH	0.023	1,751	0.023	1,754	0	1,365	131	3,119	131
	Total	1.000	111,889	1.001	112,053	102,771	20,593	10,426	132,646	113,198
CG in PADD II	HCs	0.980	112,210	0.963	110,216	110,216	17,066	12,957	127,282	123,173
	MTBE	0.020	1,871	0.020	1,837	1,032	263	0	2,101	1,032
	Total	1.000	114,081	0.982	112,053	111,248	17,329	12,957	129,382	124,205
CG with No Ether	HCs	1.000	114,500	0.979	112,053	112,053	17,350	13,173	129,403	125,227
	Total	1.000	114,500	0.979	112,053	112,053	17,350	13,173	129,403	125,227

TABLE 3 Relative RFG Volumes and Energy Content[a]

Fuel Type	Total Energy Use[b]	Total Oil Use[b]
RFG with MTBE at 2.1% O_2	1.000	1.000
RFG with ETBE at 2.1% O_2	1.013	0.982
RFG with Ethanol at 2.1% O_2	1.060	1.094
RFG Mix No. 1 (70% RFG with MTBE at 2.1% O_2; 30% RFG with ETOH at 2.1% O_2)	1.018	1.025
RFG Mix No. 2 (70% RFG with MTBE at 2.1% O_2; 30% RFG with ETOH at 2.7% O_2)	1.020	1.021
CG in PADD II	0.995	1.120
CG with No Ether	0.995	1.130

[a] Based on last two columns of Table 2.

[b] Compared with RFG with MTBE at 2.1% O_2 (base case).

Column 5 presents, for each gasoline type, the volume required to deliver the same total energy (see column 6) as is delivered by a gallon of RFG with MTBE at 2.1% oxygen. This RFG type (with MTBE) serves as the baseline for this analysis. The RFGs are actually very similar in terms of the volume of fuel required to deliver the same energy. As expected, because of the addition of oxygen and subsequent lower energy content of RFG, a greater volume of RFG is required than is the case with conventional gasoline.

3.2 FEEDSTOCK REQUIREMENTS

The remaining analysis is based on the fuel volumes presented in Column 5 of Table 2, which are the volumes of each fuel required to deliver equal energy. Column 7 presents the crude oil content of the various gasolines. The estimates of crude oil content

TABLE 4 Oxygen, Alcohol, and Energy Content of Oxygenates and Hydrocarbons

Item	Oxygen/ Alcohol Content (%)	Item	Energy Content (Btu/gal)
Oxygen Content in RFG		Ethanol	75,670
		Methanol	56,560
2.1% O_2	13.30 ETBE	Isobutylene	94,000
	11.67 MTBE	ETBE	96,926
	6.00 Ethanol	MTBE	93,528
2.7% O_2	17.10 ETBE	HCs Typical in RFG	114,500
	15.00 MTBE		
	7.71 Ethanol	Butane	95,038
Alcohol Content of Ethers			
ETBE	42.5		
MTBE	33.9		

take into account the feedstock used to produce these components, but not the process energy requirements. The crude oil contents of the various components of gasoline are provided in Table 5.

The hydrocarbon portion of gasoline is assumed to come from 100% crude oil feedstock. In fact, some natural gas (as hydrogen) and some natural gas liquids are used as feedstocks, and their proportion in the final fuel may vary across gasoline formulations. We have not accounted for this potential shift in feedstock. The NGLs themselves can be made from crude oil, thereby complicating the analysis of such a shift.

The crude oil content of ETBE and MTBE reflects the crude oil feedstock used to produce the isobutylene component of these ethers. Ethanol and methanol have no crude oil content. Isobutylene may be produced from crude oil or NGLs. In this analysis, we assume that all isobutylenes produced outside the refinery and used to make ethers outside the refinery are derived from NGLs. These NGLs, in turn, are assumed to be derived from natural gas-related sources, not crude oil. This assumption is consistent with the definitions of the 1992 Energy Policy Act (EPACT). In EPACT, ethers (and, implicitly, the NGLs used in the production of ethers) are defined as "replacement fuels" or fuels that are "substantially not petroleum" (Section 301).

The isobutylenes used within the refinery to produce ethers are treated as oil-derived because it is most likely that they will be derived from crude oil within the refinery. Although this treatment is not strictly consistent with EPACT definitions, we believe that it accurately reflects the actual processing path.

TABLE 5 Crude Oil Content of Oxygenates (Crude Oil Feedstock)[a]

Component/Fuel	Crude Oil Content (%)	Production of Ether and Isobutylene: Internal (share)	Production of Ether and Isobutylene: External (share)	Oil Feedstock for Isobutylene: Internal (share)	Oil Feedstock for Isobutylene: External (share)
Ethanol	0	-	-	-	-
Methanol	0	-	-	-	-
Isobutylene					
For ETBE in RFG	7.5	-	-	-	-
For MTBE in RFG	7.5	0.075	0.925	1	0
For MTBE used with ethanol in mixed RFG pools	2.0	0.02	0.98	1	0
For MTBE in CG	71.0	0.71	0.29	1	0
ETBE	5.2	-	-	-	-
MTBE Only in RFG	5.9	-	-	-	-
MTBE Used with Ethanol in Mixed RFG Pools	1.6	-	-	-	-
MTBE in CG	56.2	-	-	-	-
Hydrocarbons	100.0	-	-	-	-

[a] Based on refinery LP run results for internal ether production vs. purchase from outside sources.

The derivation of the proportion of isobutylene used within the refinery to produce ethers is based on estimates developed in the NPC Refining Study (NPC 1993). For that study, TM developed estimates of the materials that would be used in the production of various gasolines, both conventional and reformulated. Table 6 gives several TM estimates of the raw materials that would be used in the refinery to produce the MTBE needed for RFG and CG production. The listing of MTBE as a "raw material" implies that it (and its isobutylene content) is produced outside the refinery. Where methanol is listed as a "raw material," it is assumed that the isobutylene used with this methanol to produce MTBE is produced in the refinery.

We estimate that, for the case where all the RFG contains MTBE, 7.5% of the ethers will be produced within the refinery. For the RFG with MTBE that is part of the product mix

TABLE 6 Refinery Products, Fuels Usage, and MTBE Raw Materials for PADD II Gasoline: 2000

Item	Base Case, No CAAA (Case Q9)	100% RFG, MTBE Only (Case S6)	100% RFG, 30% ETOH (Case S13H)
Products (Bbl/d)			
Gasoline	1.682E+06	1.713E+06	1.717E+06
(% ether or ethanol)	2	12	10
Diesel	6.820E+05	6.820E+05	6.820E+05
Jet fuel	2.050E+05	2.050E+05	2.050E+05
Subtotal	2.569E+06	2.600E+06	2.604E+06
Plant fuel burned	2.306E+05	1.855E+05	2.007E+05
Other	3.620E+05	3.775E+05	4.293E+05
Total	3.162E+06	3.163E+06	3.234E+06
Fuels Used for Production (Bbl/d FOE[a])			
Plant fuel burned	2.306E+05	1.855E+05	2.007E+05
Natural gas purchased	3.290E+04	6.820E+04	7.090E+04
Electricity	4.021E+04	3.763E+04	4.183E+04
(kWh/d)	2.490E+07	2.330E+07	2.590E+07
Total (FOE)	3.037E+05	2.913E+05	3.134E+05
Raw Materials for MTBE			
MTBE	1.000E+04	1.840E+05	1.390E+05
Methanol	8.000E+03	5.000E+03	1.000E+03
Total MTBE used	3.400E+04	1.990E+05	1.420E+05

[a] FOE: fuel oil equivalent.

Sources: Turner, Mason, and Co. (Table F-3, Jan. 8, 1993, draft; Table Y-1, March 30, 1993, draft) and unpublished information.

containing 30% RFG with ethanol, the TM estimates suggest that just 2% of the ether and isobutylene are produced within the refinery. These levels of internal ether production may appear lower than expected, but they are consistent with other process changes within the refinery related to the production of severely reformulated gasoline. Most important is the demand for C_4S for alkylation, which might otherwise have been used for ether production. As the hydrocarbon portion of the RFG is even more severely reformulated to achieve additional VOCs reductions to offset the higher RVP of ethanol-blended RFG, the refinery shifts farther away from internal ether production. Finally, we estimate that 71% of the smaller volume of MTBE produced for use with conventional gasoline in PADD II is produced internally.

No separate runs were performed by TM for the RFG made with ETBE. In this analysis, we assume that the crude oil feedstock for isobutylene used in the production of

ETBE is the same as that for MTBE only. Because the alcohol contents of ETBE and MTBE differ, the crude oil contents of the ethers themselves will differ, as shown in Table 5.

The lowest crude oil content of all the fuels delivering equal energy is calculated to be that of RFG with ETBE, and the next-lowest is that of RFG with MTBE only. The two product mixes that include ethanol use more crude oil feedstock, and the RFG with ethanol only uses the most crude oil feedstock. All five RFGs, of course, reduce crude oil use when compared with that of conventional gasoline.

3.3 PROCESS ENERGY REQUIREMENTS

Estimates of the energy and crude oil required to produce the components of the various gasolines were derived from several sources. This section addresses the production of the individual components first and then discusses the total energy required to produce the final fuels.

3.3.1 Energy and Crude Oil Required to Produce Hydrocarbons

As indicated above, TM refinery LP model runs were used to determine the energy and materials that would be used in the production of various fuels (see Tables A.1 and A.2 in the Appendix). Table 6 provides a summary of the key results. The estimates were used to determine the amounts of energy and oil required to produce HCs. In all the runs for RFG and conventional gasolines, it was assumed that all the plant fuel, natural gas, and electricity used in the refinery were used to produce the HCs for motor gasoline, diesel fuels, and jet fuel; these three fuels represent more than 75% of the products of the refinery. The diesel and jet fuel product volumes were held constant between the various RFG and conventional fuel runs, and all the runs resulted in the production of equal amounts of gasoline energy for vehicular propulsion. Any differences in the energy and oil required per gallon of HCs produced are attributed to the different processing requirements of the various RFGs. The results of the analysis of these runs are presented in Table 7. Some very small shifts in other products occurred, but these are not accounted for in this analysis.

The energy required to produce the HCs used in the mixed RFG pool is greater than for those used in the RFG with MTBE only, because the HCs must be more severely processed to achieve the incremental VOCs reductions needed to offset the VOCs increase associated with ethanol use. Ethanol has a higher blending RVP than MTBE, which, if no other adjustments are made, increases the VOCs level of the final fuel. Additional processing of the HC components is required to achieve a lower RVP level and maintain the same overall VOCs level.

No separate runs for RFG with ethanol only were made. The HCs in this RFG would have to be even more severely processed than those in the mixed RFG pool, and additional measures taken as well, to produce an RFG that maintained the required VOCs reduction.

TABLE 7 Calculation of Refinery Fuel Used to Produce HCs (LP Runs Only)

Production/Consumption	Base Case, No CAAA (Case Q9)	100% RFG, MTBE Only (Case S6)	100% RFG, 30% ETOH (Case S13H)
HCs Produced			
Total HCs			
Bbl/d	2.535E+06	2.400E+06	2.434E+06
gal	1.065E+08	1.008E+08	1.022E+08
Diesel/jet only			
Bbl/d	8.870E+05	8.870E+05	8.870E+05
gal	3.725E+07	3.725E+07	3.725E+07
Gasoline only			
Bbl/d	1.648E+06	1.513E+06	1.547E+06
gal	6.923E+07	6.353E+07	6.497E+07
Total Energy in Plant Fuel Burned to Produce HCs (Btu)			
Total HCs	1.433E+12	1.153E+12	1.248E+12
Diesel/jet only[a]	5.015E+11	5.015E+11	5.015E+11
Gasoline only	9.319E+11	6.516E+11	7.461E+11
Unit Energy in Plant Fuel Burned to Produce HCs			
Total HCs (Btu/gal produced)	1.346E+04[b]	-	-
Diesel/jet only[a] (Btu/gal produced)	1.346E+04[b]	1.346E+04	1.346E+04
Gasoline only			
Btu/gal produced	1.346E+04[b]	1.026E+04	1.148E+04
Btu/Btu HC produced	0.118	0.090	0.100
Total Energy Used in Refineries to Produce HCs (Btu)			
Total HCs	1.888E+12	1.811E+12	1.948E+12
Diesel/jet only[a]	6.605E+11	6.605E+11	6.605E+11
Gasoline only	1.227E+12	1.150E+12	1.288E+12
Unit Energy Used in Refineries to Produce HCs			
Total HCs (Btu/gal produced)	1.773E+04[b]	-	-
Diesel/jet only[a] (Btu/gal produced)	1.773E+04[b]	1.773E+04	1.773E+04
Gasoline only			
Btu/gal produced	1.773E+04[b]	1.811E+04	1.982E+04
Btu/Btu HC produced	0.155	0.158	0.173

[a] Energy in plant fuel burned, natural gas, and electricity to produce diesel and jet fuel is held constant across runs.

[b] Energy in plant fuel burned, natural gas, and electricity to produce HCs in conventional gasoline is assumed to be the same for gasoline, diesel fuel, and jet fuel.

We assume that the increased energy required to produce such HCs (over the HCs for the base RFG with MTBE) would be approximately three times the difference between the energy production requirements of the pool (which is 30% ethanol) and the base RFG. The results obtained when this assumption is made are shown in Table 8. We make the same assumption for the plant fuel share of the total energy production requirements.

Alternatively, the use of ETBE in RFG allows the refiner to use higher-RVP HCs (approximately 0.5 higher RVP), because ETBE has a substantially lower blending RVP than does MTBE. Use of these higher-RVP HCs should, at a minimum, result in lower plant fuel requirements, because the lighter (higher-RVP) components can be used rather than requiring additional processing to obtain lower-RVP components. No refinery LP model runs for RFG with any ETBE mix were made, but an estimate of the energy required to produce HCs for RFG with ETBE was derived by examining the energy required to produce two RFGs with a 0.4-RVP delta in their gasoline pool properties; the RVPs of the gasolines examined are 7.2 and 6.8. The energy required to produce these RVPs may be greater than needed for this analysis, but the focus is on the *difference* between the two. We estimate a difference of 250 Btu per gallon of HC produced. The TM runs examined were Case VLQ40 V. Low and Case LQ40 Low (see Tables A.3 and A.4 in the Appendix). PADD III runs were used in this analysis because similar runs were not made for PADD II. Use of a 0.4-RVP delta rather than 0.5 RVP slightly understates this potential benefit of the use of ETBE.

Table 8 presents summary estimates for all four RFGs, plus conventional gasoline. It shows that more total energy is required, in general, to produce each HC used in RFGs. There is considerable variation among the RFGs, the energy requirement for RFG made with ethanol being much higher than that for RFG made with ethers.

TABLE 8 Plant Fuel Burned and Other Purchased Fuels to Produce HCs

Fuels	Energy in Plant Fuel Burned, Natural Gas, and Electricity to Produce HCs (Btu/Btu HC produced)	Energy in Plant Fuel Burned to Produce HCs (Btu/Btu HC produced)
Base Case	0.155	0.118
RFG with MTBE Only	0.158	0.090
RFG with 70% MTBE and 30% ETOH	0.173	0.100
RFG with ETBE Only	0.156	0.087
RFG with ETOH Only	0.208	0.125

Some energy and crude oil will be required to make the isobutylene for ether produced within the refinery. We have implicitly included that energy requirement in this calculation of energy needed to produce HCs for RFG. To avoid doublecounting in the estimate of the energy required to produce ethers for RFG (which includes ether production, both internal and external to the refinery), we subtract an estimate of that internal energy use.

3.3.2 Energy and Crude Oil Required to Produce MTBE

Table 9 presents estimates of the energy and crude oil required to produce MTBE. These estimates are based on a report by Chem Systems, Inc. (1992), which provides estimates of the amount of plant energy required for various MTBE production processes. We assume use of the process in which MTBE is produced from field butanes (see Table A.5 in the Appendix). Feedstock for the plant energy and feedstock for the butanes and methanol are estimated on the basis of the Chem Systems report and a report on greenhouse gas emissions by DeLuchi (1991).

We assume that the energy ratio of natural gas feedstock to methanol produced is 1.5:1. The Chem Systems report suggests a lower ratio, but the one we are using is consistent with sources cited by DeLuchi. We assign all the ether plant energy use to the production of the ether; we do not account for the fuel-gas by-products that are also produced. Finally, we assume that the energy required to produce the field butanes and natural gas used in the system is negligible.

As indicated above, some MTBE will be produced within the oil refinery. Table 10 presents the final energy requirements to produce MTBE, as a weighting of the energy required to produce MTBE within the refinery (and thus, without MTBE plant energy) and the energy required to produce MTBE in the MTBE plant.

3.3.3 Energy and Crude Oil Required to Produce Ethanol

The energy requirements for corn and ethanol production are derived from a paper by Marland and Turhollow (1991) that provides estimates of the energy and crude oil required to produce ethanol without accounting for by-products of the ethanol production process. However, Marland and Turhollow also provide estimates of the CO_2 emissions associated with ethanol production that do account for by-products. We examined the latter estimates in order to account for by-products in this analysis of the energy and crude oil associated with ethanol production. Turhollow (1993) has indicated that the proportion of gross CO_2 emissions that Marland and Turhollow (1991) had assigned to by-products could also be applied to the energy and crude oil use associated with the production of ethanol.

TABLE 9 MTBE Production Field Butanes (500,000 metric ton/yr capacity)

Utility or Feedstock Input	Enthalpy of Steam (Btu/lb steam)	Units per Metric Ton MTBE	Energy Content (10^6 Btu/ unit input)	Energy to Produce Feedstock (10^6 Btu/ unit input)	Total Energy Input		Plant Energy Only (Btu/gal MTBE)	Feedstock for Plant Energy Only (Btu/gal MTBE)	Feedstock for Field Butanes and MEOH Only (Btu/gal MTBE)	Total Energy to Produce Feedstock Only (Btu/gal MTBE)	Fuel Type for Production Energy
					10^6 Btu/ metric ton MTBE	Btu/gal MTBE					
Steam, 600 psi (ton)	1,380	0.67	2.760	0.585	2.24	6,314	5,209	1,105	-	1,105	Natural gas
Electricity (kWh)	NA	40.56	0.003	0.007	0.42	1,170	390	780	-	780	All fuel sources
Natural Gas (10^6 kcal)	NA	0.07	3.968	-	0.28	782	782	0	-	0	Natural gas
Field Butanes (metric ton)	NA	0.7655	42.957	-	32.88	92,630	-	-	0	0	Natural gas
Methanol (metric ton)	NA	0.3658	18.778	9.389	10.30	29,024	-	-	9,675	9,675	Natural gas
Total						1[illegible]9 920	6,381	1,885	9,675	11,559	

Source: Chem Systems (Table A4-40, 1992); DeLuchi (Table J-1, 1991).

TABLE 10 Weighted Energy Requirements for Ether Production

Fuel/Oxidant	Energy Required per Btu of Ether Produced (Btu)	
	Energy	Oil
MTBE Only in RFG	0.187	0
MTBE Used with Ethanol in Mixed RFG Pools	0.190	0
MTBE in CG	0.143	0
ETBE Only	0.326	0.024

Turhollow has provided two sets of estimates for the allocation of by-product credits: one derived by using the displacement method and one by using the value method. The displacement method is generally more accepted than the value method (Turhollow 1993) and more appropriate for an energy-based analysis. We use the displacement method. We estimate that 11% of the energy and crude oil estimated to be required to produce ethanol should be assigned to the production of by-products. Consequently, we estimate that for every Btu of ethanol produced, approximately 0.8 Btu is required to produce it, and one-tenth of that energy is based on the use of crude oil (see Table 11).

The Marland and Turhollow estimates are representative of current industry best practice. Ethanol produced to meet incremental RFG demand may be nearer to industry average, and thus more energy-intensive, than indicated here.

3.3.4 Energy and Crude Oil Required to Produce ETBE

We adapted the MTBE production process to develop estimates of the ETBE production process (Table 12). This process may slightly understate ETBE process energy, because additional distillation steps are required in ETBE production to achieve the required water removal. The major adaptation is the substitution of the energy required to produce ethanol for that required for methanol. As with MTBE, we assume that some ETBE will be produced within the refinery and some outside. The weighted estimate of the energy required to produce the ETBE is also given in Table 10.

3.3.5 Energy and Crude Oil Required to Produce Fuels

Columns 8 and 9 of Table 2 provide the final estimates of the energy and crude oil required to produce the various RFGs and conventional gasolines.

TABLE 11 Energy Required to Produce Ethanol Only, Higher Heating Value

By-Products	Energy Content of Ethanol (Btu/gal)	Energy Required to Produce Ethanol: Btu/gal — Energy	Btu/gal — Oil Only	Btu/Btu ETOH Produced — Energy	Btu/Btu ETOH Produced — Oil Only
Accounted for	84,186	65,547	6,292	0.779	0.075
Not Accounted for	84,186	73,814	7,086	-	-

Source: Marland and Turhollow (1991).

3.4 TOTAL ENERGY AND CRUDE OIL REQUIRED (at 2.1% Oxygen)

Columns 10 and 11 of Table 2 give the estimates of the total energy required to deliver equal energy for propulsion by using year 2000 RFG (at 2.1 % oxygen). If RFG used with MTBE is the base fuel, the results presented in this table and Table 3 indicate that the least energy-intensive of the RFG options is RFG with MTBE only. RFG with ETBE and the mixed RFG pools require approximately 1.3-2.0% more energy. RFG with ethanol requires nearly 6% more total energy. The least crude oil used to deliver equal energy for propulsion is with RFG with ETBE: 1.8% less than the base RFG. The mixed RFG pools increase the use of crude oil over the base by 2.1-2.5%. RFG with ethanol increases crude oil use by more than 9%. All these RFGs require more total energy than conventional gasoline, but all use less crude oil than conventional gasoline.

3.5 RFGs PRODUCED IN 1995

The analysis reported above has focused on year 2000 RFGs. We also developed an approximation of the differences in energy and crude oil required to produce RFGs in 1995, because the EPA rulemaking also affects these RFGs. Only two RFGs are examined: (1) RFG with MTBE only and (2) a mixed RFG pool with ethanol and MTBE. We focused on the *differences*, rather than on the totals, because we lacked the refinery LP model runs needed to provide a complete characterization of the materials used in or to produce the 1995 RFGs.

We analyzed only the effects of the difference in RVP of the HCs used in these RFGs. To accommodate the increase in RVP associated with the use of ethanol, the RVP of the HCs in the mixed RFG pool would have to be 0.3 RVP lower than the RVP of the RFG with MTBE only. In the analysis of the energy required to produce RFG with ETBE (reported above), we estimated that a 0.4-RVP increase in the RVP of HCs used with ETBE (over HCs used in another RFG) would mean a reduction in energy (and crude oil) requirements of 250 Btu per gallon of HC produced. We use this same estimate here, but in reverse. A 0.3-RVP decrease is estimated to require an increase of 190 Btu per gallon of HC produced.

TABLE 12 ETBE Production, Adapted from MTBE Production

Utility or Feedstock Input	Enthalpy of Steam (Btu/lb steam)	Units per Metric Ton ETBE	Energy Content (10^6 Btu/ unit input)	Energy to Produce Feedstock (10^6 Btu/ unit input)	Total Energy Input: 10^6 Btu/ metric ton ETBE	Total Energy Input: Btu/gal ETBE	Plant Energy Only (Btu/gal ETBE)	Feedstock for Plant Energy Only (Btu/gal ETBE)	Feedstock for Field Butanes and MEOH Only (Btu/gal ETBE)	Total Energy to Produce Feedstock Only (Btu/gal ETBE)	Fuel Type for Production Energy
Steam, 600 psi (ton)	1,380	0.67	2.760	0.585	2.24	6,386	5,268	1,118	-	1,118	Natural gas
Electricity (kWh)	NA	40.56	0.003	0.007	0.42	1,183	394	789	-	789	All fuel sources
Natural Gas (10^6 kcal)	NA	0.07	3.968	-	0.28	791	791	0	-	0	Natural gas
Field Butanes (metric ton)	NA	0.69	42.957	-	29.64	84,446	-	-	0	0	Natural gas
Ethanol (metric ton)	NA	0.425	25.198	19.619	19.05	54,266	-	-	23,755	23,755	9.6% oil
Total						147,072	6,454	1,906	23,755	25,662	

Source: Adapted from Table 9.

Factoring this increase in the energy and crude oil required to produce HCs into our calculations of total energy and crude oil required to produce the mixed RFG pool, we found that the pool would require 0.8% more total energy to deliver equal VMT and 2.0% more total crude oil than the RFG with MTBE only. These impacts are slightly less than for the same mixed RFG pool in 2000, which is consistent with the additional severity of the reformulation required in 2000.

4 ENERGY AND CRUDE OIL REQUIRED TO PRODUCE GASOLINE OXYGENATED AT 2.7% LEVEL

Tables 13 and 14 provide estimates of the energy and crude oil required to produce gasoline with a 2.7% oxygen content by weight. This oxygen-content level is required in CO nonattainment areas for a portion of the year (typically four to five months). Areas requiring the use of RFG year-round will require that the oxygen-content level of the RFG be raised during these months (CO control program RFG). Areas not using RFG will simply require CO control program oxygenated gasoline (OG). Averaging of gasolines with higher and lower oxygen-content levels is permitted, so long as the 2.7% level is maintained.

The estimates presented in Tables 13 and 14 are derived from the estimates for gasolines produced with a 2.1% oxygen content level, which are discussed in Section 3. No separate refinery LP model runs were conducted to develop these estimates. The only difference assumed between the RFGs with 2.1% oxygen content and those with 2.7% oxygen content is the proportion of the oxygenates and HCs in the final fuel. The energy required to produce each "HC Btu" and "oxygenate Btu" is assumed to be the same as for the RFG with 2.1% oxygen content.

For a given oxygenate, the volume of oxygenate required to achieve the 2.7% oxygen-content level is the same whether the gasoline is an RFG or an OG. The energy required to produce the HC portion differs, however. We assume that the energy required to produce the HCs in OG is not significantly different than that required to produce HCs in conventional gasoline, as estimated in Tables 7 and 8. In reality, the HCs in OG tend to be 2-3 octane numbers lower than the HCs in conventional gasoline, to take advantage of the high blending octane of the oxygenates. Thus, there should be some effect on the energy required to produce these lower-octane HCs, but we have not accounted for that effect.

Tables 13 and 14 indicate that OGs have lower energy requirements than do their counterpart CO control program RFGs, but the former also use more crude oil. RFG or OG made with ethanol has greater energy and crude oil use requirements than has RFG or OG made with either ether. Ethanol blends currently used (e.g., 10% ethanol) increase total energy use by 3.2% and total crude oil use by 5.8% with respect to CO control program RFG with MTBE. As before, all the fuels presented require more total energy but less crude oil for their production than does conventional gasoline.

TABLE 13 Fuel Volumes and Energy Content for 2.7% RFG

Fuel Type	Components	Initial Volume (gal)	Energy Content of Initial Volume (Btu)	Revised Volume to Deliver Equal Btu as RFG with MTBE Only at 2.1% O_2 (gal)	Revised Energy Content of Fuel (Btu)	Oil Content of Equal-Btu RFG [Feedstock] (Btu)	Energy Required to Produce Equal-Btu RFG (Btu)	Oil Required to Produce Equal-Btu RFG (Btu)	Total Energy Required to Deliver Equal-Btu RFG (Btu)	Total Oil Required to Deliver Equal-Btu RFG (Btu)
RFG with MTBE at 2.7% O_2	HCs	0.850	97,325	0.855	97,936	97,936	15,489	8,773	113,425	106,709
	MTBE	0.150	14,029	0.151	14,117	838	2,636	0	16,753	838
	Total	1.000	111,354	1.006	112,053	98,774	18,125	8,773	130,178	107,546
RFG with ETBE at 2.7% O_2	HCs	0.829	94,921	0.833	95,396	95,396	14,879	8,337	110,275	103,733
	ETBE	0.171	16,574	0.172	16,657	861	5,436	392	22,093	1,253
	Total	1.000	111,495	1.005	112,053	96,257	20,315	8,729	132,369	104,986
RFG with Ethanol at 2.7% O_2	HCs	0.923	105,667	0.927	106,187	106,187	22,038	13,268	128,225	119,455
	ETOH	0.077	5,837	0.078	5,866	0	4,567	438	10,433	438
	Total	1.000	111,505	1.005	112,053	106,187	26,605	13,706	138,659	119,893
Oxygenated Gasoline with MTBE at 2.7%	HCs	0.850	97,325	0.855	97,936	97,936	15,164	11,514	113,100	109,450
	MTBE	0.150	14,029	0.151	14,117	838	2,636	0	16,753	838
	Total	1.000	111,354	1.006	112,053	98,774	17,800	11,514	129,853	110,287
Oxygenated Gasoline with ETBE at 2.7%	HCs	0.829	94,921	0.833	95,396	95,396	14,771	11,215	110,167	106,611
	ETBE	0.171	16,574	0.172	16,657	861	5,436	392	22,093	1,253
	Total	1.000	111,495	1.005	112,053	96,257	20,207	11,607	132,260	107,864
Oxygenated Gasoline with ETOH at 2.7%	HCs	0.923	105,667	0.927	106,187	106,187	16,442	12,484	122,629	118,671
	ETOH	0.077	5,837	0.078	5,866	0	4,567	438	10,433	438
	Total	1.000	111,505	1.005	112,053	106,187	21,009	12,922	133,063	119,109
Oxygenated Gasoline with ETOH at 3.5%	HCs	0.900	103,050	0.912	104,388	104,388	16,163	12,272	120,551	116,660
	ETOH	0.100	7,567	0.101	7,665	0	5,968	573	13,633	573
	Total	1.000	110,617	1.013	112,053	104,388	22,131	12,845	134,185	117,233

TABLE 14 Relative RFG and OG Volumes and Energy Content[a]

Fuel Type	Total Energy Use[b]	Total Oil Use[b]
RFG with MTBE at 2.7% O_2	1.001	0.970
RFG with ETBE at 2.7% O_2	1.018	0.947
RFG with Ethanol at 2.7% O_2	1.066	1.082
OG with MTBE at 2.7% O_2	0.998	0.995
OG with ETBE at 2.7% O_2	1.017	0.973
OG with Ethanol at 2.7% O_2	1.023	1.075
OG with Ethanol at 3.5% O_2	1.032	1.058

[a] Based on last two columns of Table 13.

[b] Compared with RFG with MTBE at 2.1% O_2 (base case).

5 CONCLUSIONS

The analysis discussed in this report indicates that RFG requires more energy but less crude oil for its production than does conventional gasoline. The least energy-intensive of the RFG options is RFG with MTBE only. If RFG with MTBE is taken as the base fuel, RFG with ETBE and the mixed RFG pools with MTBE and ethanol (which would fulfill the EPA's February 1993 RFG NPRM) require approximately 1.3-2.0% more total energy than does the base. RFG with ethanol requires nearly 6% more total energy.

RFG with ETBE uses the least crude oil to deliver equal energy for propulsion: 1.8% less than that for the base RFG. The mixed RFG pools increase the use of crude oil over the base by 2.1-2.5%. Production of RFG with ethanol alone increases crude oil use by more than 9%.

Use of oxygenates at a 2.7% level in the CO control programs does not alter the direction of these results. CO control program OGs have lower total energy requirements than their counterpart CO control program RFGs, but the former also use more crude oil.

The specific impetus for this report was an EPA proposal that would allow RFG blended with ethanol to meet a lesser VOCs reduction standard than RFGs with other oxygenates. If implemented, the proposal would cause increased energy use of 1.8 to 2.0%, depending on the oxygen level (2.1% or 2.7%) achieved with the ethanol portion of the mixed RFG pool. Crude oil use would increase by 2.1 to 2.5%.

The results reported here are based on a number of assumptions and are focused on RFGs produced in one area of the country. Clearly, making changes in the assumptions would change the specific estimates calculated. However, we believe that the general trend of the results is likely to remain the same across regions and with all but drastic changes in production process assumptions.

REFERENCES

Chem Systems, Inc., 1992, *The Global MTBE Business*, Appendixes, July.

DeLuchi, M.A., 1991, *Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity*, Argonne National Laboratory report ANL/ESD/TM-22, Nov.

Marland, G., and A.F. Turhollow, 1991, *CO_2 Emission from the Production and Combustion of Fuel Ethanol from Corn*, Oak Ridge National Laboratory, Feb.

National Petroleum Council, 1993, *NPC Refining Study, Chapter Four: U.S. Refining Capability and Costs, Section IV* (Draft), June 30.

Turhollow, A.F., 1993, personal communication, May.

Turner, Mason, and Co., 1993, *NPC Refining Study, IIC-Summer 1995/2000 F2-SF and 4/92 CF Case Runs*, Jan.

APPENDIX:

Selected Reference Materials Used in the Analysis of the Energy Requirements for RFG Production

TABLE A.1 Refining Raw Material and Product Rate — MBPCD IIIC — Summer 1995/2000 F2 — SF and 4/92 CF Case Results NPC 1991-92 Study of U.S. Refining Industry

Raw Materials	Base Case Q9 No FCAAA	CaseS5 '95 Full Opt in	Base Case Q6 Target Δ V.O.C	Case S6 Q6 + 100% RFG	Case S6 + Hi EtOH	Case S13H S13 + S6 Δ V.O.C.
Raw Materials						
Domestic - S	1,223	1,223	1,985	1,985	1,985	1,985
HL	371	371	174	174	174	174
HH	226	226	692	692	692	692
Foreign - S	259	278	732	732	732	780
HL	166	172	669	669	669	669
HH	1,752	632	1,531	1,500	1,517	1,385
Subtotal Crudes	2,997	2,902	2,932	2,826	2,863	2,904
MTBE	10	88	100	184	127	139
Ethanol					30	30
Normal Butane	17	10				
Isobutane	22	33	36	40	49	53
Natural Gas to H2 Plant Feed	5	5	5	5	11	5
Methanol	8	8	4	5	5	1
Other Raw Materials	102	102	102	102	102	102
Total Raw Materials	3,162	3,148	3,178	3,163	3,187	3,234
Products						
Motor Gasolines						
Conventional	1,682	750	752			
Oxygenated						
Reformulated/Oxygenated						
Reformulated		950	945	1,713	1,198	1,205
CARB2					514	
Kero Jet/Kerosene	205	205	205	205	205	205
Diesel/No. 2 Fuels						
Diesel - LA, ULS						
Diesel - 0.05% S	580	580	580	580	580	580
No. 2 Fuel	102	102	102	102	102	102
No. 6. Fuel (1% Sul)	14	14	14	14	14	14
No. 6 Bunker	11	11	11	11	11	38
Marketable Coke - 400#	60	54	59	52	55	61
Catalytic Coke - 400#	52	50	50	49	50	50
Vacuum Gas Oil						
Benzene	2	2	2	2	2	2
Toluene	5	5	5	5	5	3
Heavy Aromatic Gaso						
Pentanes to P/C						
Natural Gasoline to P/C	38	38	38	36	37	39
Normal Butane			24	25	30	34
Isobutane						
Propane	98	92	94	86	90	92
Process Gas/C2/C2=,FOE	162	138	144	120	132	135
Other Products	271	271	271	271	271	271
(Gain)/Loss	(120)	(114)	(118)	(107)	(109)	(108)
Total Products	3,162	3,148	3,178	3,163	3,187	3,234
Crude Properites						
Gravity, °API	33.9	34.2	34.1	34.3	34.2	34.2
Sulfur, Wt%	1.18	1.11	1.14	1.09	1.11	1.13
Gasoline Demand Increase, %[1]						
Results		1.1	0.9	1.8	1.8	2.1
Target		1.1	0.8	1.9	1.9	2.1

[1] To maintain constant miles traveled with lower BTU content reformulated gasoline.

Source: Turner, Mason, and Co., NPC Refining Study (Table F-3, Jan. 8, 1993, draft).

TABLE A.2 Energy Balance Impacts of Ethanol at Constant ΔVOC — PADD II Summer 2000 Cases S13H vs S6[1] NPC 1991 — 93 Study of U.S. Refining Industry

	MBPCD				
	S6	S13H	Δ	BFOE/ Liq B	MBPCD FOE
Products					
Gasolines					
RFG-E		512.0	512.0	0.746	382.0
RFG-M	1,712.7	1,204.7	(508.0)	0.752	(382.0)
Subtotal	1,712.7	1,716.7	4.0		0.0
Bunker	11.0	37.8	26.8	1.00	26.8
Marketable Coke, FOE	51.8	61.1	9.3	1.00	9.3
Petrochem. Gaso.	32.1	35.2	3.1	0.69	2.1
Toluene	5.0	3.0	(2.0)	0.84	(1.7)
NC4	24.9	33.7	8.8	0.68	6.0
Propane	80.0	86.0	6.0	0.60	3.6
Plant Fuel Burned, FOE	185.5	200.7	15.2	1.00	15.2
Loss (Gain)	(104.4)	(105.2)	(0.8)		0.0
Other	1,164.6	1,164.6	0.0		0.0
Total	3,163.2	3,233.6	70.4		61.3
Raw Materials					
Crude	2,826.4	2,904.4	78.0	0.92	71.8
IC4	40.4	53.2	13.2	0.65	8.6
MTBE	184.3	138.8	(45.5)	0.62	(28.2)
Methanol	5.4	0.6	(4.8)	0.62	(1.8)
Ethanol		29.4	29.4	0.38	15.0
Nat. Gas to H2 Plant	5.1	5.2	0.1	0.51	0.1
Other	102.0	102.0	0.0	1.00	0.0
Total	3,163.2	3,233.6	70.4		65.5
Net Inputs (Raw Mat less Prod)					4.2
Utilities					
Nat. Gas Purch, FOE	68.2	70.9	2.7	1.00	2.7
Elec., MMkWh/d	23.3	25.9	2.6	1.60	4.2
Plant Fuel Burned, FOE					15.2
Total Utilities Used					22.1
Lost Energy					
Total Net Inputs plus Utilities, FOE					26.3
Percent of Energy in Gasolines [2]					6.9%
Percent of Energy in Ethanol [3]					175%

[1] S13H VOC Reduction = 41% based on 4/92 EPA CF. Gasoline pool = 30% RFG-E + 70% RFG-M
S6 VOC Reduction = 41% based on 4/92 EPA CF. Gasoline pool = 100% RFG-M.

[2] 26.3 MBPCD FOE lost/382 MBPCD FOE in gasoline switched from RFG-M to RFG-E.

[3] 26.3 MBPCD FOE lost/15 MBPCD FOE in Ethanol used.

Source: Turner, Mason, and Co., NPC Refining Study (Table Y-1, March 30, 1993, draft).

TABLE A.3 Run Basis and Reformulated Gasoline Pool Properties IIIC — Summer 2000 F2 — 4/92 CF Case Results NPC 1991-92 Study of U.S. Refining Industry

Gasoline Specs*	Base Case Q6 Target Δ V.O.C.	Base Case Q6N = Q6+ Δ Cap. Chg.	Case VLQ40 V. Low Δ V.O.C.	Case LQ40 Low Δ V.O.C.	Case HQ40 High Δ V.O.C.	Case QN2 Q6N + 10.7% OL
Aromatics, Vol. %, Maximum Avg.						
Oxygen, Wt%, Minimum Avg.	2.1	2.1	2.1	2.1	2.1	2.1
Olefins, Vol.%, Maximum Avg.						10.7
Benzene, Vol.%, Maximum Avg.	0.7	0.7	0.7	0.7	0.7	0.7
Sulfur, WPPM, Maximum Avg.						
Reid Vapor Pressure, PSI, Min	6.5	6.5	6.5	6.5	6.5	6.5
Reid Vapor Pressure, PSI, Max Regulatory Cap						
T50, °F, Maximum Avg.						
T90, °F, Maximum Avg.						
V.O.V., % Reduction	45	45	35	40	48	45
T.A.P., %Reduction	30	30	30	30	30	30
% Class C, Fixed	40	40	40	40	40	40
Ethers, V% Pool						
Purchased (Sold)						
Manufactured						
Gasoline Pool Properties						
(R+M)/2 Octane, Clear*	88.6	88.6	88.6	88.6	88.6	88.6
Aromatics, Vol.%	24.7	23.7	24.1	23.8	23.1	24.0
Ethers, Vol.%	11.7	11.7	11.7	11.7	11.7	11.7
Oxygen, Wt.%	2.1	2.1	2.1	2.1	2.1	2.1
Olefins, Vol.%	11.6	10.7	13.0	12.3	9.7	10.7*
Benene, Vol.%	0.7	0.7	0.7	0.7	0.7	0.7
Sulfur, WPPM	144	141	171	173	76	137
Reid Vapor Pressure, PSI	6.5	6.5*	7.2	6.8	6.5*	6.5*
Temperature at V/L = 20, °F	149	149	145	147	148	149
Distillation						
T10, °F	136	134	126	130	133	133
T50, °F	205	203	200	201	201	204
T90, °F	344	342	344*	346	325	344
Specific Gravity	0.746 3	0.7444	0.7433	0.7438	0.7404	0.7450
Heat Content, MBTU/G	112.1	112.0	111.7	111.8	111.7	112.0
V.O.C., gm/mile*	0.71	0.71	0.83	0.77	0.67	0.71
- % Reduction*	45	45	35	40	48	45
NO_x, index	0.97	0.97	0.99	0.98	0.95	0.96
- % Reduction	3	3	2	2	5	4
T.A.P., mg/mile	35	34	37*	36	31	35
- % Reduction	33	35	31*	36	31	35

* Input limit.

Source: Turner, Mason, and Co. (Table D1-1A, 1993).

TABLE A.4 Refining Raw Material and Product Rates — MBPCD IIIC — Summer 2000 F2 — 4/92 CF Case Results NPC 1991-92 Study of U.S. Refining Industry

Raw Materials	Base Case Q9 No FCAAA	Base Case Q6 Target Δ V.O.C.	Base Case Q6N = Q6 Δ Cap. Chg.	Case VLQ40 V. Low Δ V.O.C.	Case LQ40 Low Δ V.O.C.	Case HQ40 High Δ V.O.C.	Case QN2 Q6N + 10.7 % OL
Raw Materials							
Domestic - S	1,985	1,985	1,985	1,985	1,985	1,985	1,985
HL	174	174	174	174	174	174	174
HH	692	692	692	692	692	692	692
Foreign - S	732	732	732	732	732	780	732
HL	669	669	669	669	669	669	669
HH	1,648	1,536	1,531	1,500	1,517	1,385	1,494
Subtotal Crudes	5,900	5,788	5,783	5,752	5,769	5,686	5,746
MTBE	3	132	141	152	152	282	143
Ethanol							
Normal Butane							
Isobutane	54	46	46	46	46	81	61
Natural Gas to H2 Plant Fee	20	24	24	24	24	27	24
Methanol	21	35	32	29	29	32	31
Other Raw Materials	447	447	447	447	447	447	447
Total Raw Materials	6,445	6,472	6,473	6,449	6,466	6,555	6,453
Products							
Motor Gasolines							
Conventional	3,151	1,177	1,173	1,177	1,176		1,176
Oxygenated -							
Reformulated/Oxygenated							
Reformulated		2,008	2,009	2,015	2,014	3,221	2,009
CARB2							
Kero Jet/Kerosene	686	686	686	686	686	686	686
Diesel/No. 2 Fuels							
Diesel - LA, ULS							
Diesel - 0.05% S	940	940	940	940	940	940	940
No. 2 Fuel	289	289	289	289	289	289	289
No. 6. Fuel (1% Sul)	57	57	57	57	57	57	57
No. 6 Bunker	57	57	57	57	57	76	57
Marketable Coke - 400#	180	174	174	172	173	168	172
Catalytic Coke - 400#	97	95	94	94	94	89	90
Vacuum Gas Oil							
Benzene	21	21	21	21	21	21	21
Toluene	25	25	25	25	25	25	25
Heavy Aromatic Gaso							
Pentanes to P/C							
Natural Gasoline to P/C	134	134	134	134	134	135	134
Normal Butane	22	42	55	20	35	74	37
Isobutane	12	24	13	27	28	12	12
Propane	151	144	144	142	144	148	142
Process Gas/C2/C2=,FOE	365	338	337	334	337	323	332
Other Products	576	576	576	576	576	576	576
(Gain)/Loss	(318)	(317)	(311)	(316)	(320)	(284)	(302)
Total Products	6,445	6,472	6,473	6,449	6,466	6,555	6,453
Crude Properites							
Gravity, °API	32.8	32.9	32.9	32.9	32.9	33.0	32.9
Sulfur, Wt%	1.20	1.17	1.18	1.17	1.17	1.13	1.17
Gasoline Demand Increase, %[1]							
Results		1.1	1.0	1.2	1.2	2.2	1.1
Target		1.1	1.0	1.2	1.2	2.1	1.1

[1] To maintain constant miles traveled with lower BTU content reformulated gasoline.

Source: Turner, Mason, and Co. (Table D1-3, 1993).

TABLE A.5 Cost of Production Estimate for MTBE

PROCESS: FLDMTBE1 — COST OF PRODUCTION ESTIMATE FOR : MTBE
PRICES : MTBE1995 — PROCESS : from Field Butanes — Million Dollars

		Capital Costs	ORIG	BOOK	REPL
Plant Startup	1990				
Analysis Date	1995	Battery Limits	226.9	226.9	226.9
Location:	USGC	Offsites	90.7	90.7	90.7
Capacity:	500.00 Thousand MT/yr				
	12,699 Barrels per Day	Total Fixed Inv.	317.6	317.6	317.6
Operating Rate:	100 percent	Working Capital			27.0
Throughput:	500.00 Thousand MT/yr				

PRODUCTION COST SUMMARY		UNITS PER MT	PRICE, Dollars /UNIT	Dollars PER MT	ANNUAL COST MM Dollars	Dollars Per Gal
RAW MATERIALS	Methanol, metric ton	0.3658	200	73.2	36.58	
	Field Butanes, metric ton	0.7655	193	147.9	73.94	
	Catalyst & Chemicals		4	4.1	2.03	
	TOTAL RAW MATERIALS			225.1	112.56	0.633
BY-PRODUCT CREDITS	Fuel Gas, MM Kcal	0.72223	11	(7.6)	(3.80)	
	TOTAL BY-PRODUCT CREDITS			(7.6)	(3.80)	(0.021)
NET RAW MATERIALS				217.5	108.76	0.612
UTILITIES	Power Purchased, KWH	40.56	0.054	2.2	1.10	
	Cooling Water, M kg	179.31	0.025	4.5	2.23	
	Steam (Gas), 600 psig, ton	0.67	12.088	8.1	4.05	
	Natural Gas, MM kcal	0.07	10.516	0.8	0.38	
	TOTAL UTILITIES			15.5	7.76	0.044
VARIABLE COST OF PRODUCTION				233.0	116.52	0.655
DIRECT CASH COSTS	Labor, 32 Men	35.83 Thousand Dollars		2.3	1.15	
	Foremen, 14 Men	40.63 Thousand Dollars		1.1	0.57	
	Super., 3 Men	49.07 Thousand Dollars		0.3	0.15	
	Maint., Material & Labor	4.00 % of ISBL		18.1	9.07	
	Direct Overhead	45 % Labor & Supervision		1.7	0.84	
	TOTAL DIRECT CASH COSTS			23.6	11.78	0.066
ALLOCATED CASH COSTS	General Plant Overhead	65 % Labor & Maintenance		14.2	7.11	
	Insurance, Property Tax	1.5 % Total Fixed Investment		9.5	4.76	
	TOTAL ALLOCATED CASH COSTS			23.7	11.87	0.067
FULL CASH COST OF PRODUCTION				280.3	140.17	0.788
NONOCASH ALLOCATIONS	Depreciation	10 Years for OSBL		18.1	9.07	
		10 Years for ISBL		45.4	22.69	
NET COST OF PRODUCTION				343.9	171.93	0.967
COST PLUS	10 % RETURN ON TOTAL BOOK INV. PLUS WC			412.8	206.39	1.161
COST PLUS	20 % RETURN ON TOTAL BOOK INV. PLUS WC			481.7	240.85	1.355
COST PLUS	30 % RETURN ON TOTAL BOOK INV. PLUS WC			550.6	275.31	1.549

Source: Chem Systems, Inc. (Table A4.40, 1992).

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