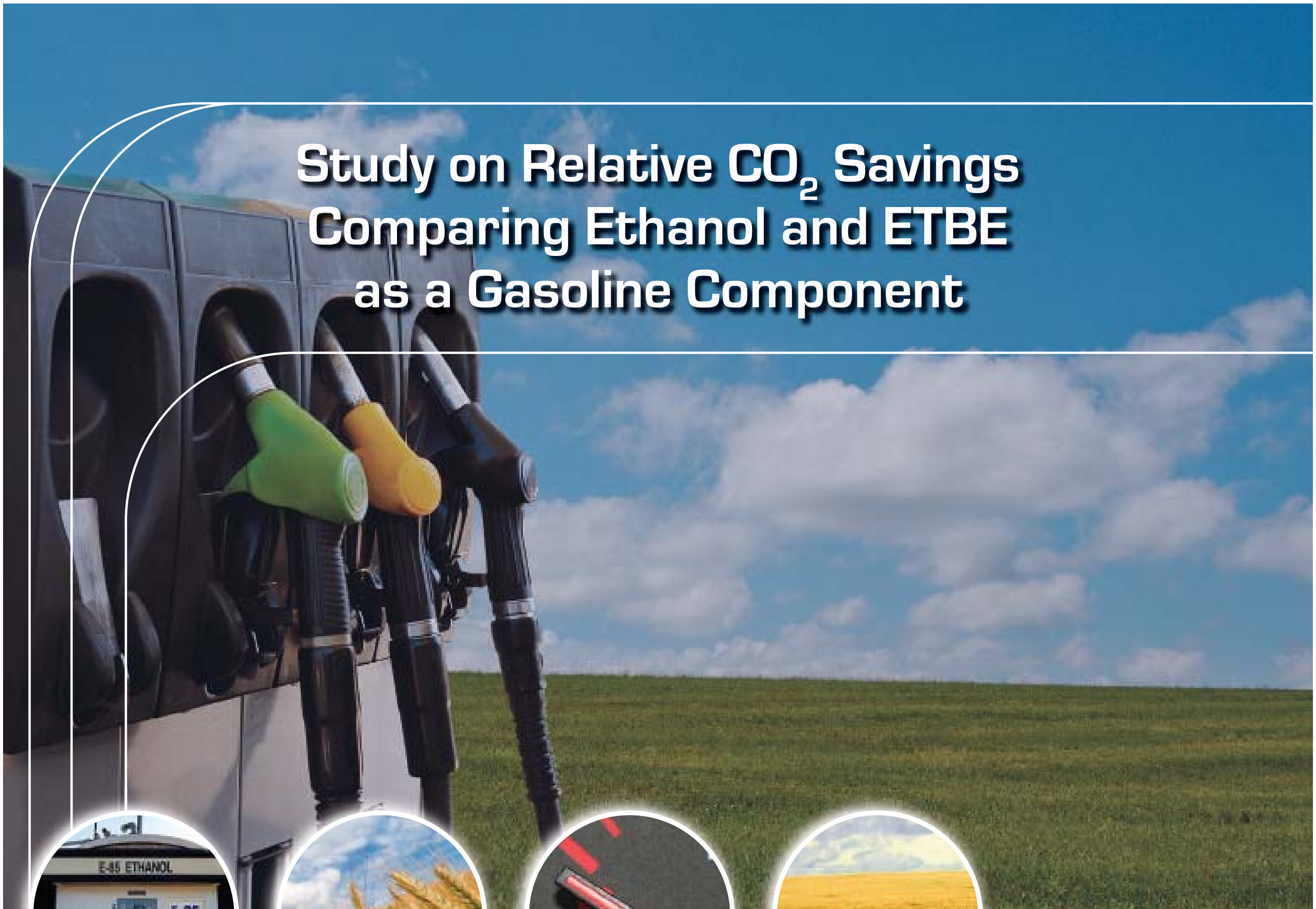
Study on Relative CO_2 Savings Comparing Ethanol and ETBE as a Gasoline Component



Submitted by:

Hart Energy Consulting

Hart Energy Consulting
1616 S. Voss, Suite 1000
Houston, Texas 77057, USA

Terrence Higgins
Executive Director, Refining & Special Studies
Hart Energy Consulting
+1.703.891.4815
thiggins@hartenergy.com

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www.hartenergy.com

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STUDY ON RELATIVE CO_2 SAVINGS COMPARING ETHANOL AND ETBE AS A GASOLINE COMPONENT

I. Executive Summary

A. Background and Objectives

Introduction of ethanol into the gasoline market will impact the processing and blending of gasoline at refineries with associated changes in operating severities, fuel consumption, product slate and product carbon. The means of introducing ethanol into gasoline, i.e., direct blend or via ETBE, will also impact the refining and blending process and resulting CO_2 effects.

A number of studies have been conducted to address the issue of CO_2 savings potential through the use of biofuels. Studies for the most part have focused on the CO_2 impacts from the production and market use of biofuels. Studies have not addressed direct blending of ethanol or the use of ETBE and the resulting CO_2 generation. These latter impacts warrant review in view of growing biofuel penetration and interest in low carbon fuels.

The objective of this study was to quantify the impacts of ethanol blending on CO_2 emissions from the refining and gasoline blending process. The study quantified CO_2 emissions from gasoline blended with ethanol and blended with ETBE, and quantified the changes in CO_2 emissions from the refinery and merchant ether plant fuel consumption. The analysis provided a relative comparison of CO_2 savings between ethanol and ETBE blending for the same quantity of ethanol.

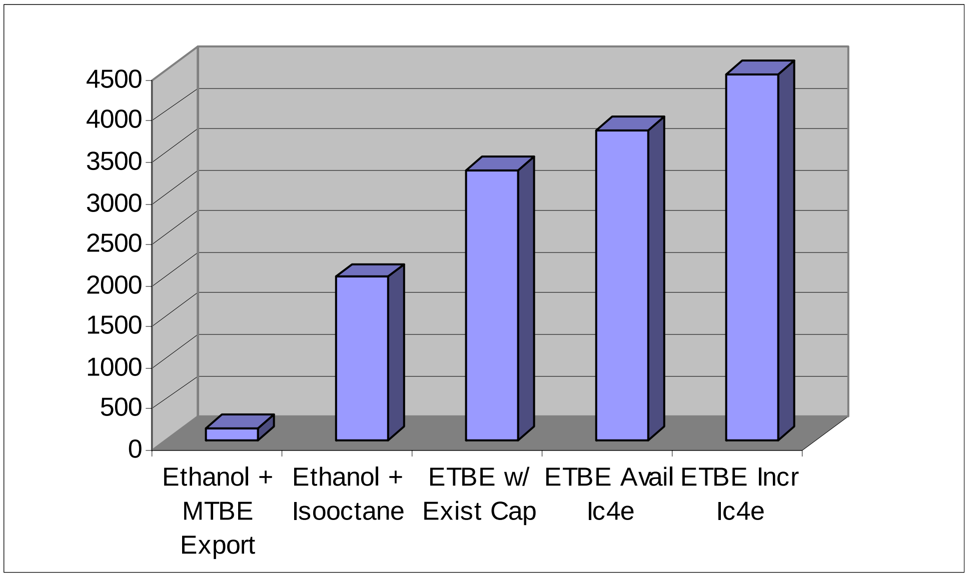
B. Summary of Results

Gasoline Manufacturing and Blending

- A Base Case 2010 was established that included 4.4 million tons/year of MTBE available for gasoline blending in Europe. Replacing the MTBE with 5.5 million tons/year ethanol (5% of EU gasoline demand), results in a small net change in refinery processing and gasoline blending operations. Crude oil requirements and refined product output are projected to undergo little change from the base case.
- The ethanol replacement case requires less refinery fuel due to the ethanol volume and octane contribution. The ethanol case also results in gasoline compositional changes. Both of these changes result in reduced CO_2 emissions.
- Replacing the ethanol with 12.1 million tons of ETBE (the ethanol mole equivalent of 5% ethanol) reduces refinery crude oil requirements and processing intensity. The ETBE case requires less refinery fuel than the base case or the ethanol case.
- The ETBE replacement case also results in large gasoline compositional changes that reduce the gasoline carbon factor and results in CO_2 emissions reductions.
- The ETBE case yields less refinery coke, which is assumed to be replaced by coal, with a small reduction in CO_2 emissions.

- Additional ethanol cases were examined with alternate assumptions with regard to MTBE production (for export) and isooctene production. ETBE cases were also run with alternate assumptions regarding the amount of ethanol converted to ETBE. The net CO_2 savings for the initial ethanol and ETBE cases and the alternate ethanol cases are shown in figure I.1.

Figure I.1: Reduction in CO_2 Emissions Relative to 2010 Base Case
Thousand Tons/Year



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- Replacing the MTBE with direct blended ethanol results in a reduction of 0.2 million tons per year of CO_2 emissions. Converting all the ethanol to ETBE results in a CO_2 reduction of 4.4 million tons per year.
- The CO_2 reduction will be impacted by alternative strategies of ethanol addition such as the volume of ethanol converted to ETBE, disposition of current MTBE production and production of isooctene. The net CO_2 savings for various direct blend ethanol and ETBE cases are shown in figure I.1.

II. Study Approach, Assumptions and Base Case

A. Overview

The impacts of ethanol and ETBE blending on CO_2 emissions were addressed with a refinery model utilized to simulate in detail Western Europe refinery processing and blending operations. The model characterized refinery processing and blending requirements for the 2010 Western European refined products market. Model results determined crude oil requirements, refined product production, processing operations, fuel consumption and product carbon content.

The output of the refinery model simulations provided the basis for evaluating the impact of ethanol and ETBE on CO_2 emissions. Emission changes were quantified by analyzing:

- changes in gasoline carbon content,
- changes in gasoline volume (required to maintain equivalent gasoline energy between cases),
- changes in carbon content and volume of other refined products,
- changes in byproduct production and disposition,
- changes in refinery fuel consumption and composition (carbon content),
- changes in hydrogen production, and
- changes in fuel consumed for the production of merchant ethers.

A base case model was developed representing Western Europe refining and refined products market for 2010. The base case Western Europe model and market were defined as that representing the EU25 along with Iceland, Norway and Switzerland. Refinery capacities were established at levels representative of 2010. In the base case, refinery and merchant MTBE/ETBE capacity was assumed to produce MTBE. No ethanol, direct blend or via ETBE was used. Need to delete "via" or reword to make sense

A series of ethanol cases were run with 5 vol% ethanol made available for gasoline blending. No MTBE or ETBE blending in EU gasoline was assumed in the ethanol cases. The initial ethanol case assumed that refinery MTBE facilities were shut down and merchant MTBE plants produce at the base case level (of refinery purchases) and export the MTBE product. Alternate ethanol cases were run with varying assumptions for merchant and refinery MTBE and/or isooctene production as follows.

- **Base Ethanol Case** with 5% ethanol available, no ether produced by refineries, merchant MTBE production at the base case level, and merchant ether production exported;
- **Ethanol 2 Case** with 5% ethanol available, refinery MTBE at the base case level, merchant MTBE production at the base case level, refinery MTBE production made available for blending in non-U.S. gasoline exports, and merchant ether production and the remaining refinery MTBE production exported;
- **Ethanol 3 Case** with 5% ethanol available, isooctene produced in refinery ether plants, and isooctene produced in converted merchant MTBE plants and made available for refinery gasoline blending.

A second series of ETBE cases were run with the same volume of ethanol available as in the ethanol cases and with the option of converting all or a portion of the ethanol to ETBE. The initial ETBE case assumed that all of the available ethanol was converted to ETBE. Alternate ETBE cases were then run with varying assumptions for capacity and conversion of ethanol to ETBE, defined as follows.

- **Base ETBE Case** with 5% ethanol available and all converted to ETBE, refinery MTBE production switched to ETBE and merchant plants converting the remaining ethanol available to ETBE;
- **ETBE 2 Case** with 5% ethanol available, available refinery and merchant isobutylene converted to ETBE, remaining ethanol available blended directly to gasoline;
- **ETBE 3 Case** with 5% ethanol available, existing refinery and merchant ether capacity utilized for ETBE production and remaining ethanol blended directly to gasoline.

The ethanol and ETBE cases held petrol and other major refinery products constant (on an energy equivalent basis). Liquefied petroleum gas (LPG) and refinery coke were allowed to vary as needed by refining simulations and model economics.

Assumptions utilized for the study and the base case parameters and simulation results are presented under B and C of this Section. The component supply and demand and model results for the ethanol and ETBE cases are then summarized in section III. The CO_2 impacts for these cases are presented in section IV.

B. Assumptions

Major assumptions utilized for the study include:

- The study time frame focused on 2010.
- Crude volume was permitted to vary. The base crude mix was representative of crude processed in Europe and variations in crude were represented by incremental Urals crude.
- All oxygenate was assumed to be smart blended, i.e., final gasoline blends after oxygenate addition met finished gasoline specifications.
- A 60 Kpa gasoline was produced with no ethanol waiver.
- Ethanol blending of 5 vol% was used.
- European gasoline consisted of two grades (98 RON and 95 RON) with the 98 RON making up about 6% of the pool.
- Gasoline export levels were set at estimated 2010 levels with U.S. exports oxygen free and other exports allowed to use MTBE in cases where MTBE was produced.
- The U.S. reformulated gasoline (RFG) exports were produced for final ethanol addition in the U.S. A portion of U.S. conventional gasoline export was produced for ethanol addition and the remainder was finished conventional gasoline.
- No expansion of refinery capacity was allowed with the exception of alkylation capacity. Alkylation capacity was allowed to expand up to 5% in the base ethanol case, with a capital charge incurred for any expansion.

- Gasoline CO_2 emissions were calculated as the product of gasoline carbon factor and the CO_2/carbon weight ratio (details are provided in Appendix 1).
- Jet fuel and diesel CO_2 changes were calculated in a similar fashion as discussed in appendix 1.
- Gasoline, jet fuel and diesel energy content was tracked and the models produced a constant energy equivalent volume of these products between cases (details are provided in Appendix 1).

C. Base Case

Table II.1 provides a projection of Western Europe refined product demand, showing demand trends between 2006 and 2010. Gasoline demand will continue to decline, falling by over 6% between 2006 and 2010. Much of the decline will be the result of further dieselization of the automotive fleet. Diesel demand will increase by 13%. Jet fuel will also grow by about 13%. There will be little change in other products.

Table II.1: Western Europe Refined Product Demand: 2006-2010
Million Tons/Year

	2006	2010
Gasoline	111	104
Naphtha	46	48
Jet Fuel/Kerosene	55	61
Diesel	186	211
Other Distillate	110	97
Residual Fuel	94	93
LPG	23	23
Other	76	77
Total	**698**	**716**

Source: Hart analysis based on International Energy Agency (IEA) data

Table II.2 presents the 2010 refined product supply and demand, showing imports and the amount of refined product demanded from refineries. Surplus gasoline will be produced, most of which will be exported to the U.S.

The base case refinery input is summarized in table II.3, and an MTBE purchase, production and blending balance is provided in table II.4. Refinery output is summarized in table II.5.

Table II.2: Western Europe Refining Input/Output: 2010
Million Tons/Year

	Demand	Imports	Refinery Production
Gasoline	104	-32	136
Naphtha	48	8	40
Jet Fuel/Kerosene	61	11	50
Diesel	211	23	188
Other Distillate	97	5	92
Residual Fuel	93	-3	96
LPG	23		23
Other	77		77

Source: Hart analysis based on International Energy Agency (IEA) data

Table II.3: Western Europe Refining Input: 2010
Million Tons/Year

	Input
Crude Oil	
Indigenous	176
API	*37.3*
% Sulfur	*0.33*
Imported	491
API	*33.7*
% Sulfur	*1.21*
Ethanol	0
MTBE	2.4
Methanol	0.7
Biodiesel	10.2
Gasoline Components	9.7
Other Unfinished Oils	10.9

Source: Hart analysis based on International Energy Agency (IEA) data

Table II.4: Base Case MTBE Purchases, Production and Blending
Thousand Tons/Year

	ThousandTons/Year
Purchases	
Merchant MTBE	2450
Ethanol	0
Production	
MTBE	1990
Ethanol to ETBE	0
ETBE	0
Gasoline Blending	
MTBE	4440
Ethanol	0
ETBE	0

Source: Hart analysis based on International Energy Agency (IEA) data

Table II.5: Western Europe Refining Output: 2010
Million Tons/Year

	Output
Gasoline	
98 RON EU Grade	5.8
95 RON EU Grade	98.5
U.S. RFG Export	5.2
U.S. Conventional Export	18.3
Other Export	8.0
Naphtha	40.5
BTX Chemicals	10.9
Jet Fuel	49.9
Distillate	
Diesel 10 ppm	187.8
Other Distillate	92.4
Residual Fuel	96.2
Lube/Asphalt	24
MTBE(1)	2.0
TAME(1)	0.1

Note: (1) Refinery production for gasoline blending; included in gasoline production
Source: Hart analysis based on IEA data and model output

In the base case, 2,450 thousand tons per year of MTBE are produced from merchant ether plants and another 1,990 thousand tons per year are produced in the refinery. The total MTBE accounts for about 3% of the total gasoline production (EU gasoline plus exports). The MTBE blended into EU gasoline makes up about 4.3% of the EU gasoline.

Gasoline qualities and blend compositions are provided in tables II.6 and II.7. The product qualities are at or close to the limits.

Table II.6: Base Case Gasoline Qualities

	EU Gasoline	Exports
Specific Gravity	0.74	0.72
Sulfur (PPM)	10	10
RVP (Kpa)	60.0	60.0
Olefin (vol%)	6.5	15.0
Aromatics (vol%)	34.8	34.6
Benzene (vol%)	0.9	0.9
Research Octane	95.3	96.0
Motor Octane	85.9	86.3

Source: Hart refinery model output

Table II.7: Base Case Gasoline Blend Composition

	EU Gasoline	Exports
Butane	5.0	4.7
Light Naphtha	7.2	21.6
Isomerate	11.5	2.0
Lt FCC Gaso	14.6	8.5
Hv FCC Gaso	2.8	32.9
Reformate	42.1	20.0
Alkylate	10.0	2.7
MTBE	4.3	0.8
ETBE	0.0	0.0
Ethanol	0.0	0.0
Isooctene	0.0	0.0
Other	2.5	6.8

Source: Hart refinery model output

Table III.8 summarizes refinery capacities and utilization for the base case. Refinery capacities are utilized at close to maximum for most primary downstream processes.

Table II.8: Base Case Refinery Capacities and Utilization

	Capacity	Utilization
Crude Distillation	762	667
Naphtha HDT	145	127
Isomerization	21	12
Reforming	98	85
Kero/Distillate HDT	297	276
Heavy Oil HDT	66	59
Hydrocracking	70	61
FCC	130	119
FCC Naph. HDT	25	23
Alkylation	13	11
Coking	20	17
MTBE	2	2
ETBE	0	0
Isooctene	0	0

Source: Hart analysis, Oil and Gas Journal, Hart model output

III. Ethanol and ETBE Case Supply, Demand and Model Results

Summary of Ethanol Cases

The gasoline component supply and demand for the ethanol cases examined are summarized in table III.1. The table shows merchant ether, ethanol and isooctene production, refinery purchases, refinery production, components used in gasoline blending and the remaining volume exported. The base case and ethanol case definitions were provided in the previous section.

Except for the ethanol 3 isooctane case, merchant MTBE production is held constant. In the base case the merchant MTBE is used for gasoline blending. In all other cases, merchant MTBE is assumed to be exported.

Table III.1: Gasoline Component Purchases, Production and Blending: Ethanol Cases
Thousand Tons/Year

	Base		Ethanol Base Case		Ethanol 2	Ethanol 3
Merchant Production						
MTBE	2450		2450		2450	0
Ethanol	0		5480		5480	5480
Ethanol to ETBE						
ETBE	0		0		0	0
Isooctene	0		0		0	1500
Purchases						
Merchant MTBE	2450		0		0	0
Ethanol	0		5480		5480	5480
Merchant ETBE	0		0		0	0
Isooctene	0		0		0	1500
Production						
MTBE	1990		0		1710	0
Ethanol to ETBE	0		0		0	0
ETBE	0		0		0	0
Isooctene	0		0		0	1090
Gasoline Blending						
MTBE	4440		0		870	0
Ethanol	0		5480		5480	5480
ETBE	0		0		0	0
Isooctene	0		0		0	2590
Exports						
Merchant MTBE	0		2450		2340	0
Refinery MTBE	0		0		840	0

Source: Hart analysis based on International Energy Agency (IEA) data

Tables III.2 and III.3 summarize refinery input and output for the ethanol cases. Table III.3 also shows refinery ether and isooctene production and blending for each case.

Table III.2: Refinery Input: Ethanol Cases
Million Tons/Year

		Base		Ethanol Base Case		Ethanol 2	Ethanol 3
Crude Oil							
	Indigenous	176		176		176	176
	API	*37.3*		*37.3*		*37.3*	*37.3*
	% Sulfur	*0.33*		*0.33*		*0.33*	*0.33*
	Imported	491		491		491	490
	API	*33.7*		*33.7*		*33.7*	*33.7*
	% Sulfur	*1.21*		*1.21*		*1.21*	*1.21*
Ethanol		0		5.5		5.5	5.5
MTBE		2.4		0		0	0
ETBE		0		0		0	0
Isooctene		0		0		0	1.5
Methanol		0.7		0		0.7	0
Biodiesel		10.2		10.2		10.2	10.2
Gasoline Components		9.7		9.7		9.7	9.7
Other Unfinished Oils		10.9		10.9		10.9	10.9

Source: Hart analysis based on International Energy Agency (IEA) data

Table III.3: Refinery Output: Ethanol Cases
Million Tons/Year

What does the superscript 1 in the highlight below refer to?

		Base		Ethanol Base Case		Ethanol 2	Ethanol 3
Refinery Production/Sales							
Gasoline							
	98 RON EU Grade	5.8		5.9		5.9	5.9
	95 RON EU Grade	98.7		99.9		998	99.7
	U.S. RFG Export	5.2		5.2		5.2	5.2
	U.S. Conventional Export	18.3		18.3		18.3	18.3
	Other Export	8.0		8.0		8.0	8.0
Naphtha		40.5		40.5		40.5	40.5
BTX Chemicals		10.9		10.9		10.9	10.9
Jet Fuel		49.9		49.9		49.9	49.9
Distillate							
	Diesel 10 ppm	187.8		187.8		187.8	187.8
	Other Distillate	92.4		92.4		92.4	92.4
Residual Fuel		96.2		96.2		96.2	96.2
Lube/Asphalt		24		24		24	24
LPG		19		20		20	21
MTBE		0		0		0.9	0
Refinery Production/Blending[1]							
MTBE		2.0		0		1.1	0
ETBE		0		0		0	0
Isooctene		0		0		0	1.3
TAME		0.1		0.1		0.1	0.1

Source: Hart analysis and Hart refinery model output

The EU gasoline production varies between the cases. The variation is due to variations in the per unit energy content of the gasoline produced. Volumes were adjusted between cases to maintain constant gasoline on an energy equivalent basis. Table III.4 provides calculated EU gasoline energy content and total gasoline energy for the ethanol cases. Variations in energy content for jet fuel and diesel were insignificant and no volume adjustments were made.

Table III.4: Gasoline Energy Content: Ethanol Cases

	Base	Ethanol Base case	Ethanol 2	Ethanol 3
EU Gasoline - Million Tons/Year	104.5	105.8	105.7	105.6
Energy Content - MJ/kg	42.72	42.24	42.24	42.27
Gasoline Energy - PJ/Year	4470	4470	4470	4470

Source: Hart refinery model output

The lower energy content of ethanol requires that additional gasoline be produced in the ethanol cases to maintain constant gasoline energy supply. Although ethanol is a low carbon fuel and will generate lower CO_2 emissions than hydrocarbon gasoline, the higher gasoline demand required to maintain constant energy offsets the benefits of the low carbon characteristics of ethanol. The impacts are quantified in Section IV.

Table III.5 and III.6 summarize the gasoline qualities and blend compositions for the ethanol cases. The most significant quality impact is on aromatics content (high carbon factor and thus higher contributor to CO_2 emissions). The aromatics content in the ethanol cases is around 1% below the base case. The lower aromatic content will result in lower CO_2 emissions per ton of gasoline.

The gasoline compositions in table III.5 show a significant drop in butane for the ethanol cases. The higher ethanol volatility required that butane be backed out to meet RVP specification.

Table III.7 summarizes refinery capacity utilization for the ethanol cases. The base case utilizations are also included for reference. In the base ethanol case, an additional 5% alkylation capacity was provided (as noted in the assumptions of Section II) and utilization was thus higher.

Table III.5: Gasoline Qualities: Ethanol Cases

	Base Case		Ethanol Base Case	
	EU Gasoline	**Exports**	**EU Gasoline**	**Exports**
Specific Gravity	0.74	0.72	0.75	0.72
Sulfur (PPM)	10	10	10	10
RVP (Kpa)	60.0	60.0	60.0	60.0
Olefin (vol%)	6.5	15.0	6.9	15.0
Aromatics (vol%)	34.8	34.6	33.9	34.6
Benzene (vol%)	0.9	0.9	0.9	0.9
Research Octane	95.3	96.0	95.3	96.0
Motor Octane	85.9	86.3	85.3	86.3
	Ethanol 2		**Ethanol 3**	
	EU Gasoline	**Exports**	**EU Gasoline**	**Exports**
Specific Gravity	0.75	0.72	0.75	0.72
Sulfur (PPM)	10	10	10	10
RVP (Kpa)	60.0	60.0	60.0	60.0
Olefin (vol%)	6.7	15.0	6.4	15.0
Aromatics (vol%)	33.9	34.6	32.9	34.6
Benzene (vol%)	0.9	0.9	0.9	0.9
Research Octane	95.3	96.0	95.3	96.0
Motor Octane	85.3	86.3	85.3	86.3

Source: Hart refinery model output

Table III.6: Gasoline Blend Composition: Ethanol Cases

	Base Case		Ethanol Base Case	
	EU Gasoline	Exports	EU Gasoline	Exports
Butane	5.0	4.7	3.1	5.3
Light Naphtha	7.2	21.6	6.6	23.0
Isomerate	11.5	2.0	12.0	0.0
Lt FCC Gaso	14.6	8.5	15.0	7.4
Hv FCC Gaso	2.8	32.9	4.7	27.0
Reformate	42.1	20.0	41.4	23.9
Alkylate	10.0	2.7	9.7	5.5
MTBE	4.3	0.8	0.0	0.0
ETBE	0.0	0.0	0.0	0.0
Ethanol	0.0	0.0	4.9	0.0
Isooctene	0.0	0.0	0.0	0.0
Other	2.5	6.8	2.6	7.9
	Ethanol 2		Ethanol 3	
	EU Gasoline	Exports	EU Gasoline	Exports
Butane	3.0	5.3	3.1	5.6
Light Naphtha	5.3	26.6	7.7	19.8
Isomerate	12.5	0.0	12.4	0.0
Lt FCC Gaso	15.7	5.4	14.7	5.7
Hv FCC Gaso	2.8	32.3	3.2	30.6
Reformate	45.1	13.2	39.2	27.5
Alkylate	9.7	3.6	10.9	0.0
MTBE	0.0	2.6	0.0	0.0
ETBE	0.0	0.0	0.0	0.0
Ethanol	4.9	0.0	4.9	0.0
Isooctene	0.00	0.0	1.4	4.2
Other	1.0	11.0	2.5	6.6

Source: Hart refinery model output

Table III.7: Refinery Capacity Utilization: Ethanol Cases

Million Tons/Year

	Base	Ethanol Base Case	Ethanol 2	Ethanol 3
Crude Distillation	667	667	667	666
Naphtha HDT	127	127	124	125
Isom (C5/C6)	12	11	12	12
Reforming	85	86	86	85
Kero/Distillate HDT	276	253	253	252
Heavy Oil HDT	59	59	59	59
Hydrocracking	61	61	61	61
FCC	119	119	119	119
FCC Naph. HDT	23	23	22	21
Alkylation	11	12	11	11
Coking	17	17	17	17
MTBE	2	0	2	0
ETBE	0	0	0	0
Isooctene	0	0	0	1

Source: Hart analysis, Oil and Gas Journal, Hart refinery model output

Summary ETBE Cases

The gasoline component supply and demand for the ETBE cases examined are summarized in Table III.8. As in the previous section, the table shows merchant ether and ethanol production, refinery purchases, refinery production, and components used in gasoline blending. For the ETBE cases there are no component exports or isooctene production.

Tables III.9 and III.10 summarize refinery input and output for the ETBE cases. Table III.10 also shows refinery ether and isooctene production and blending for each case.

Table III.8: Gasoline Component Purchases, Production and Blending: ETBE cases
Thousand Tons/Year

	Base		ETBE Base Case		ETBE 2	ETBE 3
Merchant Production						
MTBE	2450		0		0	0
Ethanol	0		5480		5480	5480
Ethanol to ETBE			-4030		-1490	-1290
ETBE	0		8880		3290	2840
Isooctene	0		0		0	0
Purchases						
Merchant MTBE	2450		0		0	0
Ethanol	0		1450		3980	4190
Merchant ETBE	0		8880		3290	2840
Isooctene	0		0		0	0
Production						
MTBE	1990		0		0	0
Ethanol to ETBE	0		-1450		-1590	-1040
ETBE	0		3200		3510	2300
Isooctene	0		0		0	0
Gasoline Blending						
MTBE	4440		0		0	0
Ethanol	0		0		2390	3150
ETBE	0		12,080		6800	5140
Isooctene	0		0		0	0
Exports						
Merchant MTBE	0		0		0	0
Refinery MTBE	0		0		0	0

Source: Hart analysis based on International Energy Agency (IEA) data

Table III.9: Refinery Input: ETBE Cases
Million Tons/Year

	Base		ETBE Base Case		ETBE 2	ETBE 3
Crude Oil						
Indigenous	176		176		176	176
API	*37.3*		*37.3*		*37.3*	*37.3*
% Sulfur	*0.33*		*0.33*		*0.33*	*0.33*
Imported	491		485		486	487
API	*33.7*		*33.7*		*33.7*	*33.7*
% Sulfur	*1.21*		*1.21*		*1.21*	*1.21*
Ethanol	0		1.4		4.0	4.2
MTBE	2.4		0		0	0
ETBE	0		9.0		3.3	2.8
Isooctene	0		0		0	0
Methanol	0.7		0		0	0
Biodiesel	10.2		10.2		10.2	10.2
Gasoline Components	9.7		9.7		9.7	9.7
Other Unfinished Oils	10.9		10.9		10.9	10.9

Source: Hart analysis based on International Energy Agency (IEA) data

Table III.10: Refinery Output: ETBE Cases
Million Tons/Year

	Base		ETBE Case		ETBE 2	ETBE 3
Refinery Production/Sales						
Gasoline						
98 RON EU Grade	5.8		5.9		5.9	5.9
95 RON EU Grade	98.5		99.3		99.5	99.6
U.S. RFG Export	5.2		5.2		5.2	5.2
U.S. Conventional Export	18.3		18.3		18.3	18.3
Other Export	8.0		8.0		8.0	8.0
Naphtha	40.5		40.5		40.5	40.5
BTX Chemicals	10.9		10.9		10.9	10.9
Jet Fuel	49.9		49.9		49.9	49.9
Distillate						
Diesel 10 ppm	187.8		187.8		187.8	187.8
Other Distillate	92.4		92.4		92.4	92.4
Residual Fuel	96.2		96.2		96.2	96.2
Lube/Asphalt	24		24		24	24
LPG	19		20		19	19
MTBE	0		0		0	0
Refinery Production/Blending[1]						
MTBE	1.7		0		0	0
ETBE	0		3.2		3.5	2.3
Isooctene	0		0		0	0
TAME	0.1		0.1		0.1	0.1

Source: Hart analysis and model output

Table III.11 provides calculated EU gasoline energy content and total gasoline energy for the ETBE cases. As with the ethanol cases, lower energy content of ETBE results in lower energy ETBE blended gasoline and thus additional gasoline is required to maintain constant gasoline energy. Variations in energy content for jet fuel and diesel were insignificant and no volume adjustments were made.

Table III.11: Gasoline Energy Content: ETBE Cases

	Base	ETBE Base case	ETBE 2	ETBE 3
EU Gasoline - Million Tons/Year	104.5	105.2	105.4	105.5
Energy Content - MJ/kg	42.72	42.44	42.36	42.33
Gasoline Energy - PJ/Year	4470	4470	4470	4470

Source: Hart refinery model output

Table III.12 and III.13 summarize the gasoline qualities and blend compositions for the ETBE cases. The most significant quality impact is on aromatics content (high carbon factor and thus higher contributor to CO_2 emissions), as was seen in the ethanol cases. For ETBE, the aromatics change is far more significant than in the ethanol cases (3% to 5% reduction vs. about 1% for ethanol.)

Table III.14 summarizes refinery capacity utilization for the ethanol cases. The base case utilizations are also included for reference.

Table III.12: Gasoline Qualities: ETBE Cases

	Base Case		ETBE Base Case	
	EU Gasoline	Exports	EU Gasoline	Exports
Specific Gravity	0.74	0.72	0.74	0.72
Sulfur (PPM)	10	10	10	10
RVP (Kpa)	60.0	60.0	60.0	60.0
Olefin (vol%)	6.5	15.0	6.4	15.0
Aromatics (vol%)	34.8	34.6	29.1	34.6
Benzene (vol%)	0.9	0.9	0.9	0.9
Research Octane	95.3	96.0	95.3	96.0
Motor Octane	85.9	86.3	85.6	86.3
	ETBE 2		ETBE 3	
	EU Gasoline	Exports	EU Gasoline	Exports
Specific Gravity	0.74	0.72	0.74	0.72
Sulfur (PPM)	10	10	10	10
RVP (Kpa)	60.0	60.0	60.0	60.0
Olefin (vol%)	7.0	15.0	7.0	15.0
Aromatics (vol%)	30.9	34.6	31.8	34.6
Benzene (vol%)	0.9	0.0	0.9	0.0
Research Octane	95.3	96.0	95.3	96.0
Motor Octane	85.3	86.3	85.3	86.3

Source: Hart refinery model output

Table III.13: Gasoline Blend Composition: ETBE Cases

	Base Case		ETBE Base Case	
	EU Gasoline	Exports	EU Gasoline	Exports
Butane	5.0	4.7	4.4	4.6
Light Naphtha	7.2	21.6	7.5	20.1
Isomerate	11.5	2.0	13.2	0.0
Lt FCC Gaso	14.6	8.5	14.7	6.2
Hv FCC Gaso	2.8	32.9	2.5	26.7
Reformate	42.1	20.0	33.8	27.8
Alkylate	10.0	2.7	7.6	3.8
MTBE	4.3	0.8	0.0	0.0
ETBE	0.0	0.0	11.5	0.0
Ethanol	0.0	0.0	0.0	0.0
Isooctene	0.0	0.0	0.0	0.0
Other	2.5	6.8	4.8	10.8
	ETBE 2		**ETBE 3**	
	EU Gasoline	**Exports**	**EU Gasoline**	**Exports**
Butane	3.9	5.1	3.6	5.3
Light Naphtha	7.1	20.1	7.6	20.1
Isomerate	13.1	0.4	13.2	0.0
Lt FCC Gaso	16.0	5.9	15.4	5.6
Hv FCC Gaso	1.4	28.6	1.8	31.5
Reformate	38.3	28.6	38.3	26.2
Alkylate	9.5	3.9	9.6	3.9
MTBE	0.0	0.0	0.0	0.0
ETBE	6.5	0.0	4.9	0.0
Ethanol	2.1	0.0	2.9	0.0
Isooctene	0.0	0.0	0.0	0.0
Other	2.1	7.4	2.7	7.4

Source: Hart refinery model output

Table III.14: Refinery Capacity Utilization: ETBE Cases
Million Tons/Year

	Base	ETBE Base Case	ETBE 2	ETBE 3
Crude Distillation	667	661	662	664
Naphtha HDT	127	117	120	123
Isom (C5/C6)	12	13	13	12
Reforming	85	79	83	83
Kero/Distillate HDT	276	253	253	253
Heavy Oil HDT	59	59	59	59
Hydrocracking	61	61	61	61
FCC	119	119	119	119
FCC Naph. HDT	23	19	20	21
Alkylation	11	9	11	11
Coking	17	15	15	16
MTBE	2	0	0	0
ETBE	0	3	4	3
Isooctene	0	0	0	0

Source: Hart analysis, Oil and Gas Journal, Hart refinery model output

IV. CO_2 Impacts

Gasoline and Refinery CO_2 Impacts

Oxygenate addition will impact gasoline blending and quality and refinery processing requirements. These blending/refining impacts will result in increasing and decreasing CO_2 emissions from various emission sources:

- Lower oxygenate carbon content will lower gasoline CO_2 emissions.
- Lower oxygenate energy content will increase gasoline volume requirements, increasing gasoline CO_2 emissions.
- Oxygenate blending will result in other fuel composition changes (e.g., lower aromatics) which will tend to lower gasoline carbon content.
- Oxygenates lower refinery octane requirements, reducing refinery fuel requirements and associated CO_2 emissions.
- Lower octane requirements will reduce gasoline reforming throughput. Additional refinery hydrogen will be required from on-purpose hydrogen generation, increasing CO_2 emissions.

Tables IV.1 and IV.2 summarize refinery CO_2 emission impacts for the ethanol and ETBE cases, respectively. Impacts are quantified for products or other refining activities where ethanol or ETBE use impacts CO_2 emissions. The CO_2 changes are shown for changes in gasoline production/quality, refinery fuel and incremental refinery hydrogen requirements.

Gasoline production was held constant on an energy basis. This resulted in a small variation in production between cases as discussed previously and indicated in tables IV.1 and IV.2.

In the ethanol cases, gasoline carbon content was reduced, while total gasoline volume increased to maintain constant gasoline energy supply. The result is a net increase in gasoline CO_2 emissions in the Ethanol Base Case and Ethanol Case 2. Gasoline composition changes with the higher volume of isooctene in the last case (Ethanol 3) offset other increases from lower energy and higher gasoline volume.

Refinery processing and fuel requirements are lower with the ethanol addition due to the additional ethanol volume and octane. Overall there is a net decrease in gasoline plus refinery CO_2 emissions.

In the ETBE cases (as with ethanol), gasoline carbon content was reduced, while total gasoline volume increased to maintain constant gasoline energy supply. For the ETBE cases, the change in carbon content is slightly higher than the ethanol cases because of the higher volume of oxygenate used (ETBE vs. ethanol). The ETBE cases also are slightly more favorable than ethanol in terms of energy content.

The refinery fuel requirement is significantly lower in the ETBE cases because of the additional volume and octane available. On the other hand, hydrogen production requirements increase because of lower reforming requirements. Hydrogen-related emissions offset some of the CO_2 emission reductions from fuel consumption.

Table IV.1: Gasoline, Refinery Fuel and H_2 Production CO_2 Emissions: Ethanol Cases

	Base		Ethanol Base Case		Ethanol 2	Ethanol 3
Gasoline Consumption						
Thousand Tons/Year	104,500		105,800		105,700	105,600
Gasoline CO_2 Emissions						
Carbon Factor	0.862		0.853		0.853	0.853
CO_2 Tons/Year	330,400		330,800		330,700	330,200
Refinery Fuel						
PJ/Year	1610		1610		1600	1600
CO_2 Tons/Year	112,200		112,000		111,600	111,300
Hydrogen Generation						
MMSCF/Year	1,049,000		1,048,000		1,053,000	1,045,000
CO_2 Tons/Year	27,900		27,900		28,000	27,800

Source: Hart refinery model output

Table IV.2: Gasoline, Refinery Fuel and H_2 Production CO_2 Emissions: ETBE Cases

	Base		ETBE Base Case		ETBE 2	ETBE 3
Gasoline Consumption						
Thousand Tons/Year	104,400		105,200		105,400	105,500
Gasoline CO_2 Emissions						
Carbon Factor	0.862		0.850		0.851	0.852
CO_2 Tons/Year	330,400		327,900		328,900	329,400
Refinery Fuel						
PJ/Year	1610		1560		1580	1590
CO_2 Tons/Year	112,200		109,300		110,200	110,600
Hydrogen Generation						
MMSCF/Year	1,049,000		1,086,000		1,073,000	1,056,000
CO_2 Tons/Year	27,900		28,900		28,500	28,100

Source: Hart refinery model output

CO_2 Impacts of Merchant Component Production and Byproduct Variations

There are also potential CO_2 impacts outside the refinery. First, merchant MTBE, ETBE or isooctene production and methanol production will generate CO_2 emissions from processing. There are also potential CO_2 impacts due to refinery byproduct production. Increases in refinery coke production are assumed to supply the fuel market, replacing coal as the incremental fuel. The impact on CO_2 emissions are calculated as the energy equivalent CO_2 emission difference between coke and coal.

Tables IV.3 and IV.4 summarizes other (outside the refinery) CO_2 emission impacts for the ETBE and ethanol cases, respectively. For the ethanol cases, merchant process emissions from MTBE or isooctene production do not change. Methanol emissions are reduced in these cases where MTBE production is lowered and eliminated. There is no change in byproduct CO_2 emissions. For the ETBE base case, there is a large increase in merchant process emissions due to higher ether production and fuel associated with production of incremental isobutylene from field butanes. For all the ETBE cases, a CO_2 reduction is shown reflecting elimination of methanol (for MTBE) production. The ETBE cases also show a small reduction in CO_2 emissions associated with byproduct coke production.

Table IV.3: Merchant Plant Fuel and Byproduct-Related CO_2 Emissions: Ethanol Cases

	Base		Ethanol Base Case		Ethanol 2	Ethanol 3
Process Fuel CO_2 Emissions						
CO_2 Thousand Tons/Year	230		230		230	230
Methanol Production						
CO_2 Thousand Tons/Year	780		430		780	0
Byproduct Fuel Change						
CO_2 Thousand Tons/Year	1,100		1,100		1,100	1,100

Source: Hart analysis

Table IV.4: Merchant Plant Fuel and Byproduct-Related CO_2 Emissions: ETBE Cases

	Base		ETBE Base Case		ETBE 2	ETBE 3
Process Fuel CO_2 Emissions						
CO_2 Thousand Tons/Year	230		1,060		250	220
Methanol Production						
CO_2 Thousand Tons/Year	780		0		0	0
Byproduct Fuel Change						
CO_2 Thousand Tons/Year	1,100		1,000		1,000	1,000

Source: Hart analysis

The net CO_2 emission impacts are summarized in tables IV.5 and IV.6. The emissions are broken down into the gasoline, refinery fuel, hydrogen production, merchant plant fuel and other byproduct fuel substitution impacts. The CO_2 emissions in the base ethanol case are estimated to be 0.2 million tons per year below the base case. The Ethanol 2 Case is similar to the Ethanol Base Case, with CO_2 emissions 0.2 million tons per year below the base case. The final Ethanol 3 Case, with refinery and merchant isooctene production, results in CO_2 emissions 2.0 million tons/year below the base case.

The ETBE cases result in significantly greater reductions in CO_2 emissions (orders of magnitude times greater than the Ethanol Base Case). The CO_2 emission reductions are driven by the gasoline and refinery CO_2 impacts of ETBE use.

Table IV.5: Summary CO_2 Emissions: Ethanol Cases
Thousand Tons/Year

	Base		Ethanol Base Case		Ethanol 2	Ethanol 4
Gasoline Consumption	330,400		330,800		330,700	330,200
Refinery Fuel	112,200		112,000		111,600	111,300
Hydrogen Production	27,900		27,900		28,000	27,800
Merchant Plant Fuel	230		230		230	230
Methanol	780		430		780	0
Other CO_2 Impacts	1,100		1,100		1,100	1,100
Total	472,610		472,460		472,410	470,630
CO_2 vs. Base Case			-150		-200	-1,980

Source: Hart analysis and Hart refinery model output

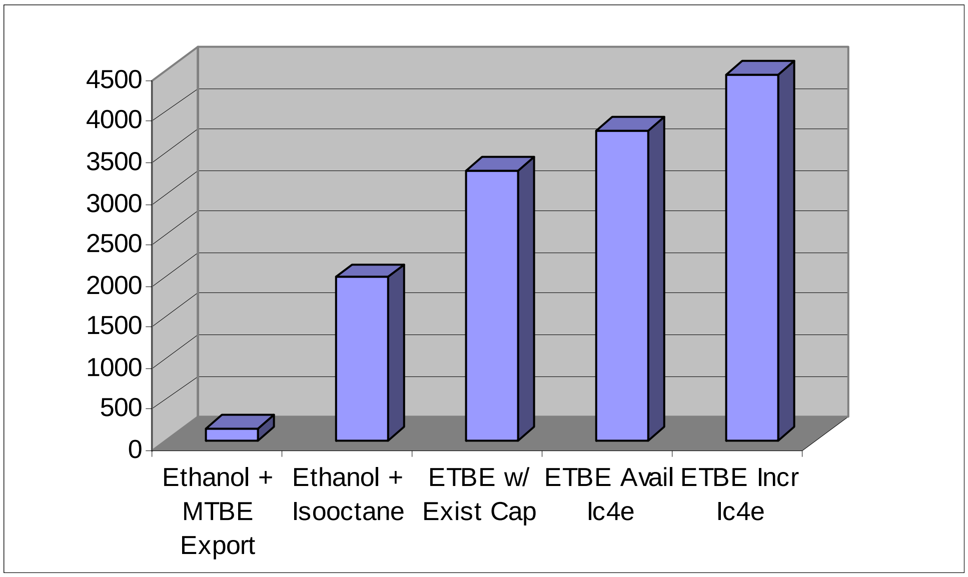
Table IV.6: Summary CO_2 Emissions: ETBE Cases
Thousand Tons/Year

	Base		ETBE Base Case		ETBE 2	ETBE 3
Gasoline Consumption	330,400		327,900		328,900	329,400
Refinery Fuel	112,200		109,300		110,200	110,600
Hydrogen Production	27,900		28,900		28,500	28,100
Merchant Plant Fuel	230		1,060		250	220
Methanol	780		0		0	0
Other CO_2 Impacts	1,100		1,000		1,000	1,000
Total	472,610		468,160		468,850	469,320
CO_2 vs. Base Case			-4,450		-3,760	-3,290

Source: Hart analysis and Hart refinery model output

Figure IV.1 displays CO_2 impacts of ethanol and ETBE cases relative to the base case. The graph provides a comparison of ethanol vs. ETBE options. Again, the ETBE option results in significantly higher CO_2 reductions as driven by gasoline and refinery CO_2 emission reductions.

Figure IV.1: CO_2 Emissions vs. Base Case Ethanol and ETBE Cases
Thousand Tons/Year



Appendix 1

This appendix provides detail on the data and methodology used to calculate gasoline and other product energy content, carbon factors and CO_2 emissions.

I. Gasoline and Gasoline Component Specific Gravity and Combustion Energy

a) General Calculation – Combustion Energy was determined as the weight average of individual component combustion energy (Enthalpy of Combustion @ 77^0F).

   Combustion Energy = $\sum c_i * LHV_i$
   Where c_i is component i
   LHV_i is the combustion energy of component i or component category i (aromatics, other non aromatic/oxygenate)

b) Component Energy – For specific chemicals included in gasoline, reported enthalpy of combustion used. These include ethanol, MTBE, butane and benzene. Component enthalpy values are shown in table A.1

c) ETBE Energy – The source data for energy values does not include ETBE. ETBE energy was estimated from reported values for other C_6 ethers. (Note from data below the energy content of MTBE is MJ/kg, which is close to that of other C_5 ethers.)

d) Aromatics Energy – Aromatic energy assumed equivalent to a mix of C_6-C_9 aromatics.

e) Other (non-oxygenate, butane, aromatics) – Energy content adjusted based on specific gravity of this portion of the gasoline. The specific gravity is calculated based on the refinery model gasoline specific gravity and the specific gravity of the above specific chemicals or chemical groups (aromatics). An energy relationship was developed based on a data base of component as follows (correlation R^2=.996):

$$LHV (MJ/L) = 39.347 (sg) + 3.576$$

f) ETBE Energy – The source data for energy values does not include ETBE. ETBE energy was estimated from reported values for other C_6 ethers. (Note from data below the energy content of MTBE is MJ/kg, which is close to that of other C_5 ethers.)

$$LHV (MJ/L) = 39.347 (sg) + 3.576$$

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Should this table be added to the TOC?

Table A.1: Component Gravity and Combustion Energy

Gasoline/Component	Specific Gravity[1] (25°)	Combustion Energy[1]	
		MJ/L	MJ/kg
Ethanol	.787	21.11	26.82
MTBE	.735	25.85	35.17
ETBE	.742[2]	26.93[3]	36.30[3]
Butane	.573	26.20	45.73
Aromatics	.863	35.28	40.85[3]
C_5 Ethers			
Ethyl Propyl Ether			35.40
Methyl sec Butyl Ether			35.28
Methyl isobutyl Ether			35.42
C_6Ethers			
n Butyl Ethyl Ether			36.46
Diisopropyl Ether			36.24
di n Propyl Ether			36.46
Aromatics			
Benzene			40.14
Toluene			40.53
o-Xylene			40.81
m-Xylene			40.81
p-Xylene			40.81
Ethyl Benzene			40.92

Note:

(1) *Source unless noted: Yows, C.L., Chemical Properties Handbook*
(2) *Estimated based on various sources*
(3) *Estimated based on other C_6 ethers*

II. Calculation of Refined Product CO_2 Emission Factors

a) General calculation – CO_2 emission factors were determined based on the estimated carbon content of the individual product:

CO_2 (Tons/Ton fuel) = CF*(44/12)

Where CF is the fraction of fuel carbon in Ton C/Ton fuel
(44/12) is the tons CO_2 combustion product per ton fuel carbon

b) Gasoline carbon fraction

i. Gasoline was characterized by percent butane, percent benzene, percent of each oxygenate (MTBE, ETBE, ethanol), and all other components. Butane, benzene and oxygenate are calculated and reported by the model. Their carbon content will be determined directly based on the chemical carbon content.

ii. The remaining gasoline (all other components) were characterized as aromatics, olefin and other. The base case gasoline carbon fraction for this portion of the gasoline will be determined as:

CF = A*.907+O*.857+P*85

Where A is the fraction of aromatics assumed to have an average carbon fraction of .905
O is the fraction of olefin assumed to have an average carbon fraction of .857
P is the fraction of paraffin, cycloparaffin and other compounds assumed to have an average carbon fraction of .85

c) Jet fuel and diesel CO_2 emissions – Jet fuel and diesel qualities varied very little between cases. Neither gravity nor aromatics content varied sufficiently to quantify a significant change in energy control.