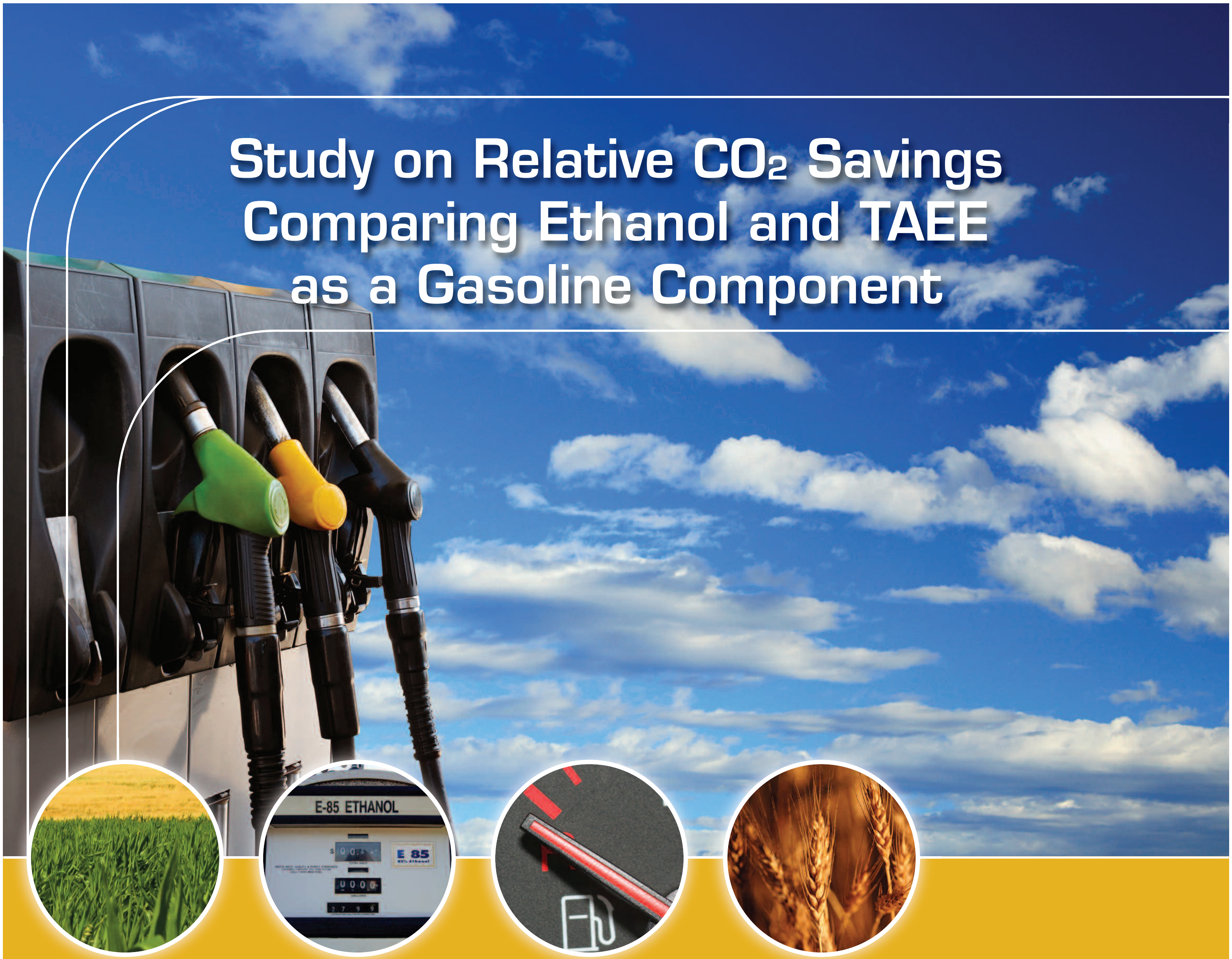
Study on Relative CO_2 Savings Comparing Ethanol and TAEE as a Gasoline Component



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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 ether (produced by combination of refinery olefin streams with ethanol), will also impact the refining and blending process. These changes in turn will impact the CO_2 emissions associated with combustion of the gasoline and with refinery fuel requirements.

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 focused on specific blending aspects of biofuels such as direct blends and etherification and the resulting CO_2 generation. These latter impacts warrant review in view of growing biofuel penetration and interest in low carbon fuels.

In 2007, Hart Energy Consulting conducted a study on behalf of the European Oxygenated Fuels Association quantifying the relative CO_2 savings of ETBE blending versus direct ethanol blending. This study expands upon that work and examines the CO_2 savings comparing TAEE and direct blend ethanol.

The objective of this TAEE 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 TAEE, and quantified the changes in CO_2 emissions from the refinery and merchant methanol plant fuel consumption. The analysis provided a relative comparison of CO_2 savings between ethanol and TAEE blending for the same quantity of ethanol.

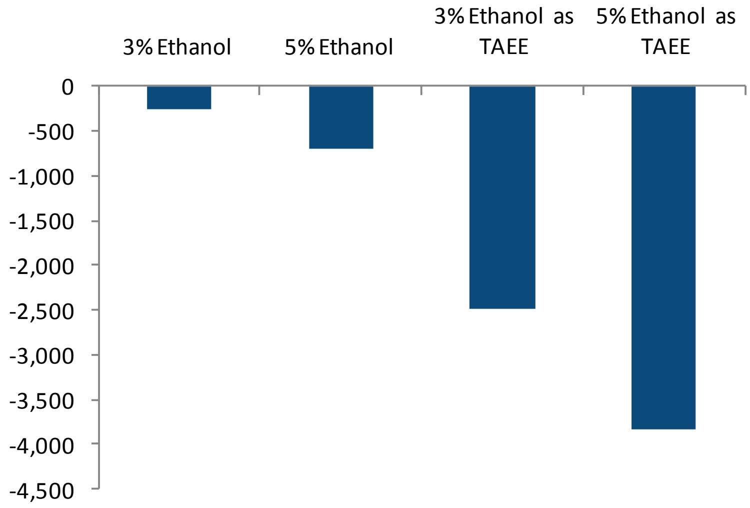
B. Summary of Results

GASOLINE MANUFACTURING AND BLENDING

- As was the case with the ETBE study, TAEE use reduces gasoline and refinery CO_2 emissions. Using TAEE results in a more favorable CO_2 impact than direct blending of ethanol.
- With total ethanol use at 5%vol in European gasoline, there is a calculated reduction in CO_2 emissions versus a base case without ethanol of 700 thousand tons per year.
- When the ethanol is blended as TAEE, the calculated reduction in CO_2 emissions versus the base case is 3830 thousand tons per year. The net CO_2 savings for the ethanol and TAEE cases analyzed (versus the base case) are shown in figure I.1.

Figure I.1: Reduction in CO_2 Emissions Relative to 2010 Base Case

Thousand Tons/Year



Source: Hart analysis and Hart refinery model output

II. Study Approach, Assumptions and Base Case

A. Overview

The impacts of ethanol and TAEE blending on CO_2 emissions were addressed with a refinery model utilized to simulate in detail European refinery processing and blending operations. The model characterized refinery processing and blending requirements for the 2010 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 TAEE 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 methanol (used in Base case).

A base case model was developed representing European refining and refined products market for 2010. The Base case European model and market were defined as that representing the EU plus Iceland, Norway and Switzerland, Eastern European countries planning for EU membership and Turkey. Refinery capacities were established at levels representative of 2010. In the base case, refinery and merchant MTBE/ETBE capacity was assumed to utilize methanol in the ether process and produce MTBE. Likewise, refinery TAME capacity was assumed to use methanol and produce TAME. No ethanol, direct blend or with ETBE/TAEE, was used.

Two subsequent ethanol cases were run with 3 vol% and 5 vol% ethanol made available for direct gasoline blending. No merchant MTBE or ETBE production/blending was made available in the ethanol cases. The ethanol cases also assumed that refinery MTBE facilities continued to operate with all production utilized for export gasoline, and TAME facilities not operated. The study Base case and Ethanol cases were defined as follows:

- **Base Case –** No ethanol, 2.01 million tons per year merchant MTBE available, 2.07 million tons per year refinery MTBE production, 0.47 million tons per year TAME production, and no merchant or refinery ETBE or TAEE production;
- **3 vol% Ethanol Case** – Ethanol available for direct blending with refinery gasoline production with the volume of ethanol equivalent to 3 vol% of European gasoline demand (3.31 million tons per year), refinery MTBE at the base case (2.07 million tons per year) level available for blending with export gasoline, no merchant MTBE production, no merchant or refinery ETBE production;
- **5 vol% Ethanol Case** - Ethanol available for direct blending with refinery gasoline production with the volume of ethanol equivalent to 5 vol% of European gasoline demand (5.34 million tons per year), refinery MTBE at the base case (2.07 million tons per year) level available for blending with export gasoline, no merchant MTBE production, no merchant or refinery ETBE production.

A second series of TAEE cases were run with the same volume of ethanol available as in the Ethanol cases and with the ethanol converted to TAEE. The Base case (same as above) and the TAEE cases were defined as follows:

- **Base Case –** No ethanol, 2.01 million tons per year merchant MTBE available, 2.07 million tons per year refinery MTBE production, 0.47 million tons per year TAME production, and no merchant or refinery ETBE or TAEE production;
- **3 vol% Ethanol as TAEE -** Ethanol converted to TAEE with the volume of ethanol equivalent to 3 vol% of European gasoline demand, refinery MTBE at the base case level available for blending with export gasoline, no merchant MTBE production, no merchant or refinery ETBE production.
- **5 vol% Ethanol as TAEE -** Ethanol converted to TAEE with the volume of ethanol equivalent to 3 vol% of European gasoline demand, refinery MTBE at the base case level available for blending with export gasoline, no merchant MTBE production, no merchant or refinery ETBE production.

Oxygenate volumes for the Base case, Ethanol cases and TAEE cases are summarized in Table II.1. In all cases ETBE volumes were assumed to be zero. While this is not representative of actual operations or market forecasts, the assumption allowed for analysis focus on the specific impacts of TAEE blending.

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

Table II.1: Base Case, Ethanol and TAEE Cases Oxygenate Volumes

	Ethanol		MTBE		TAME	TAEE
Base Case, Ethanol and TAEE	**vol%**	**Mil t/yr**	**Merchant Mil t/yr**	**Refinery Mil t/yr**	**Mil t/yr**	**Mil t/yr**
Base Case	0%	0	2.1	2.07	0.47	0
Ethanol at 3%	3%	3.3	0	2.07	0	0
Ethanol at 5%	5%	5.3	0	2.07	0	0
3% Ethanol as TAEE	3%	3.3	0	2.07	0	8.6
3% Ethanol as TAEE	5%	5.3	0	2.07	0	13.8

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 TAEE 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.
- Gasoline was held constant on an energy equivalent basis. Gasoline energy content was calculated for each run and volumes adjusted to keep total gasoline energy supply constant between cases.
- LPG, refinery fuel and coke were permitted to vary based on refinery requirements and economics. All other products were held at the Base case level with carbon/energy content monitored for variations from the Base case.
- 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 3 vol% and 5 vol% was used.
- European gasoline consisted of three grades (98 RON, 95 RON and 91 RON) with the 98 RON and 91 RON making up about 10% and 6% of the pool, respectively.
- Gasoline export levels were set at estimated 2010 levels with U.S. exports oxygen free and other exports allowed to use MTBE.
- The exports for the U.S. market were produced for final ethanol addition in the U.S.
- No expansion of refinery capacity was allowed with the exception of alkylation capacity.
- Gasoline CO2 emissions were calculated as the product of gasoline carbon factor and the CO2/carbon weight ratio (details are provided in Appendix 1).
- Jet fuel and diesel CO2 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.2 provides a projection of Western Europe refined product demand, showing demand trends between 2008 and 2010. Gasoline demand will continue to decline, falling by nearly 6% between 2008 and 2010. Much of the decline will be the result of further dieselization of the automotive fleet. Diesel demand will decrease by 4% and jet fuel will also decline by about 5%. The reduction in demand reflects the global economic recession of 2009. Refined product demand is projected to be down significantly in 2009 and for most products (except gasoline) will experience some recovery in 2009, but not back to 2008 levels.

Table II.2: European Refined Product Demand: 2008-2010

Million Tons/Year

Europe	2008	2010
Gasoline	109	102
Naphtha	47	41
Jet Fuel/Kerosene	62	59
Diesel	219	214
Other Distillate	107	107
Residual Fuel	96	94
LPG	35	34
Other	101	97
Total	**776**	**747**

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

Table II.3 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.4 and refinery output is summarized in table II.5.

Table II.3: European Supply and Demand

Million Tons/Year

Europe	Demand	Imports	Refinery Production
Gasoline	102	-38	140
Naphtha	41	7	34
Jet Fuel/Kerosene	59	12	47
Diesel	214	31	183
Other Distillate	107	5	102
Residual Fuel	94	0	94
LPG	34	4	30
Other	97	10	87

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

Table II.4: European Refining Input: 2010

Million Tons/Year

Europe	Input
Crude Oil	
Indigenous	176
° API	*37.2*
% Sulfur	*0.37*
Imported	507
° API	*33.9*
% Sulfur	*1.18*
Ethanol	0
MTBE	2.0
Methanol	0.9
Biodiesel	13.4
Gasoline Components	8.4
Other Unfinished Oils	20.2

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

Table II.5: European Refining Output: 2010

Million Tons/Year

Europe	2010 Base Case
Refinery Production/Sales	
Gasoline	
98 RON EU Grade	9.7
95 RON EU Grade	86.4
91 RON EU Grade	6.1
U.S. Export	16.7
Other Export	21.2
Naphtha	34.0
BTX Chemicals	10.9
Jet Fuel	47.4
Distillate	
Diesel 10 ppm	190.8
Other Distillate	111.9
Residual Fuel	93.9
Lube/Asphalt	24.0
LPG	18.3
Refinery Production/Blending[1]	
MTBE	2.1
TAME	0.5
TAEE	0.0

[1] *Included in gasoline production/sales*

Source: Hart analysis and model output

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

Europe	EU Gasoline	Exports
Specific Gravity	0.74	0.76
Sulfur (PPM)	10	73
RVP (Kpa)	60.0	55.0
Olefin (vol%)	6.7	5.1
Aromatics (vol%)	34.8	31.1
Benzene (vol%)	0.9	1.1
Research Octane	95.0	90.7
Motor Octane	86.5	83.0

Source: Hart refinery model output

Table II.7: Base Case Gasoline Blend Composition

Volume Percent

Europe	EU Gasoline	Exports
Butane	4.3	5.5
Light Naphtha	8.2	2.2
Isomerate	23.3	0.0
Lt FCC Gaso	13.2	3.6
Hv FCC Gaso	2.4	41.8
Reformate	39.7	14.1
Alkylate	5.9	4.4
MTBE	1.3	7.3
TAME	0.4	0.0
Ethanol	0.0	0.0
Other	1.2	21.1

Source: Hart refinery model output

Table II.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

Million Tons/Year

Europe	Capacity	Utilization
Crude Distillation	848	684
Naphtha HDT	167	120
Isom (C5/C6)	25	23
Reforming	110	84
Kero/Distillate HDT	260	250
Heavy Oil HDT	71	65
Hydrocracking	74	68
FCC	130	117
FCC Naph. HDT	23	20
Alkylation/Polymerization	14	10
Coking	25	23
MTBE	2	2
TAME	1	1
TAEE	0	0

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

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

A. Summary of Ethanol Cases

Tables III.1 and III.2 summarize refinery input and output for the Ethanol cases. Table III.2 also shows refinery MTBE, TAME and TAEE production in the refinery. The refinery MTBE, TAME and TAEE is all blended to gasoline; there is no net final product production of ethers for markets outside the refinery.

Table III.1: Refinery Input: Base Case and Ethanol Cases

Million Tons/Year

Europe	2010 Base Case	3% Ethanol No Ether	5% Ethanol No Ether
Crude Oil			
Indigenous	176	176	176
° API	*37.2*	*37.2*	*37.2*
% Sulfur	*0.37*	*0.37*	*0.37*
Imported	507	505	502
°API	*33.9*	*33.9*	*33.9*
% Sulfur	*1.18*	*1.18*	*1.18*
Ethanol	0	3.3	5.3
MTBE	2.0	0	0
Methanol	0.9	0.8	0.8
Biodiesel	13.4	13.4	13.4
Gasoline Components	8.4	8.4	8.4
Other Unfinished Oils	20.2	20.2	20.2

Source: Hart analysis and model output

There is a small reduction in crude oil requirements in the Ethanol cases largely due to the fact that a greater volume of ethanol is supplied versus the ether volume in the Base case. Crude oil requirements are also reduced some because of lower fuel requirements and higher gasoline yields in the ethanol cases. (Lower octane requirements on refinery gasoline reformer operations result in higher reformer gasoline yield). As ethanol supply is increased in the 5% vol case, crude oil requirements are further reduced.

In the refinery output table, (table III.2) only LPG and gasoline volumes vary between cases. There was also variation between cases in internal refinery fuel consumption (and production) and coke production (not shown in table III.2 but quantified in Section IV). Other products were held constant in the analysis and because no significant variations in product energy content were observed, no volume adjustments were made.

The EU gasoline production varies between the Ethanol 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.3 provides calculated EU gasoline energy content and total gasoline energy for the Ethanol cases.

Table III.2: Refinery Output: Base Case and Ethanol Cases

Million Tons/Year

Europe	2010 Base Case	3% Ethanol No Ether	5% Ethanol No Ether
Refinery Production/Sales			
Gasoline			
98 RON EU Grade	9.7	9.8	9.8
95 RON EU Grade	86.4	87.4	88.1
91 RON EU Grade	6.1	6.1	6.1
U.S. Export	16.7	16.7	16.7
Other Export	21.2	21.2	21.2
Naphtha	34.0	34.0	34.0
BTX Chemicals	10.9	10.9	10.9
Jet Fuel	47.4	47.4	47.4
Distillate			
Diesel 10 ppm	190.8	190.8	190.8
Other Distillate	111.9	111.9	111.9
Residual Fuel	93.9	93.9	93.9
Lube/Asphalt	24.0	24.0	24.0
LPG	18.3	18.2	17.9
Refinery Production/Blending[1]			
MTBE	2.1	2.1	2.1
TAME	0.5	0.0	0.0
TAEE	0.0	0.0	0.0

[1] *Included in gasoline production/sales*

Source: Hart refinery model output

Table III.3: Gasoline Energy Content: Base and Ethanol Cases

Europe	2010 Base Case	3% Ethanol No Ether	5% Ethanol No Ether
EU Gasoline - Million Tons/Year	102.2	103.3	104.0
Energy Content - MJ/Kg	42.87	42.45	42.12
Gasoline Energy - PJ/Year	4380	4380	4380

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 some of the benefits of the low carbon characteristics of ethanol. The impacts are quantified in Section IV.

The Appendix to this Section provides summaries of gasoline quality, gasoline blending and refinery capacity and utilization for both the Ethanol and TAEE cases. Table III.A.1 and III.A.2 summarize the gasoline qualities and blend compositions for the Ethanol cases and table III.A.3 summarizes refinery capacity and capacity utilization.

B. Summary TAEE Cases

Tables III.4 and III.5 summarize refinery input and output for the TAEE cases. Table III.2 also shows refinery MTBE, TAME and TAEE production in the refinery. The refinery MTBE, TAME and TAEE is all blended to gasoline; there is no net final product production of ethers for markets outside the refinery.

Table III.4: Refinery Input: Base Case and TAEE Cases

Million Tons/Year

Europe	2010 Base Case	3% Ethanol as TAEE	5% Ethanol as TAEE
Crude Oil			
Indigenous	176	176	176
° API	*37.2*	*37.2*	*37.2*
% Sulfur	*0.37*	*0.37*	*0.37*
Imported	507	501	498
° API	*33.9*	*33.9*	*33.9*
% Sulfur	*1.18*	*1.18*	*1.18*
Ethanol	0	5.3	10.7
MTBE	2	0	0
Methanol	0.9	0.8	0.8
Biodiesel	13.4	13.4	13.4
Gasoline Components	8.4	8.4	8.4
Other Unfinished Oils	20.2	20.2	20.2

Source: Hart analysis and model output

As with the Ethanol cases, there is a small reduction in crude oil requirements in the TAEE cases largely due to the fact that a greater volume of ethanol is supplied versus the ether volume in the Base case. Crude oil requirements are also reduced some because of lower fuel requirements and higher gasoline yields as in the ethanol cases. As ethanol supply is increased in the 5% vol case, crude oil requirements are further reduced. The crude requirements for the TAEE cases are slightly lower than in the Ethanol cases.

In the refinery output table, (table III.5) only LPG and gasoline volumes vary between cases. There was also variation between cases in internal refinery fuel consumption (and production) and coke production (Lower octane requirements on refinery gasoline reformer operations result in higher reformer gasoline yield). Other products were held constant in the analysis and because no significant variations in product energy content were observed, no volume adjustments were made.

The EU gasoline production varies between the TAEE cases as observed in the Ethanol 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.6 provides calculated EU gasoline energy content and total gasoline energy for the Ethanol cases.

Table III.5: Refinery Output: Base Case and TAEE Cases

Million Tons/Year

Europe	2010 Base Case	3% Ethanol as TAEE	5% Ethanol as TAEE
Refinery Production/Sales			
Gasoline			
98 RON EU Grade	9.7	9.8	9.8
95 RON EU Grade	86.4	87.0	87.7
91 RON EU Grade	6.1	6.1	6.1
U.S. Export	16.7	16.7	16.7
Other Export	21.2	21.2	21.2
Naphtha	34.0	34.0	34.0
BTX Chemicals	10.9	10.9	10.9
Jet Fuel	47.4	47.4	47.4
Distillate			
Diesel 10 ppm	190.8	190.8	190.8
Other Distillate	111.9	111.9	111.9
Residual Fuel	93.9	93.9	93.9
Lube/Asphalt	24.0	24.0	24.0
LPG	18.3	15.9	15.2
Refinery Production/Blending[1]			
MTBE	2.1	2.1	2.1
TAME	0.5	0.0	0.0
TAEE	0.0	8.6	13.8
[1] *Included in gasoline production/sales*			

Source: Hart refinery model output

Table III.6: Gasoline Energy Content: Base and TAEE Cases

Europe	2010 Base Case	3% Ethanol as TAEE	5% Ethanol as TAEE
EU Gasoline - Million Tons/Year	102.2	102.9	103.6
Energy Content - MJ/Kg	42.87	42.55	42.29
Gasoline Energy - PJ/Year	4380	4380	4380

Source: Hart refinery model output

The gasoline quality, gasoline blending and refinery capacity and utilization for the TAEE cases are summarized in the Appendix to this Section along with Ethanol case results.

Section III APPENDIX

Table III.A.1: Gasoline Qualities: Ethanol Cases

	3% vol Ethanol		5% vol Ethanol	
Europe	**EU Gasoline**	**Exports**	**EU Gasoline**	**Exports**
Specific Gravity	0.75	0.76	0.75	0.76
Sulfur (PPM)	10	73	10	37
RVP (Kpa)	60.0	55.0	60.0	55.0
Olefin (vol%)	6.9	4.6	5.9	7.0
Aromatics (vol%)	34.8	30.8	34.8	30.9
Benzene (vol%)	0.9	1.1	0.9	0.8
Research Octane	95.0	90.7	95.0	90.7
Motor Octane	85.6	83.2	85.1	82.3

Source: Hart refinery model output

Table III.A.2: Gasoline Blend Composition: Ethanol Cases

Volume Percent

	3% vol Ethanol		5% vol Ethanol	
Europe	**EU Gasoline**	**Exports**	**EU Gasoline**	**Exports**
Butane	3.5	5.7	3.5	5.1
Light Naphtha	8.2	1.8	5.2	10.9
Isomerate	20.4	0.0	16.1	0.0
Lt FCC Gaso	12.8	5.6	11.9	7.4
Hv FCC Gaso	3.3	41.9	5.1	36.1
Reformate	41.0	13.3	45.3	10.4
Alkylate	5.3	6.1	6.5	2.2
MTBE	0.0	7.3	0.0	7.3
TAEE	0.0	0.0	0.0	0.0
Ethanol	3.0	0.0	4.9	0.0
Other	2.3	18.4	1.5	20.5

Source: Hart refinery model output

Table III.A.3: Refinery Capacity Utilization: Ethanol Cases

Million Tons/Year

		3% Ethanol No Ether	5% Ethanol No Ether
Europe	**Capacity**	**Utilization**	
Crude Distillation	848	681	678
Naphtha HDT	167	123	128
Isom (C5/C6)	25	21	16
Reforming	110	85	88
Kero/Distillate HDT	260	225	225
Heavy Oil HDT	71	65	65
Hydrocracking	74	68	68
FCC	130	117	117
FCC Naph. HDT	23	13	13
Alkylation/Polymerization	14	10	10
Coking	25	23	22
MTBE	2	2	2
TAME	0	0	0
TAEE	0	0	0

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

Table III.A.4: Gasoline Qualities: TAEE Cases

Volume Percent

	3% vol Ethanol as TAEE		5% vol Ethanol as TAEE	
Europe	**EU Gasoline**	**Exports**	**EU Gasoline**	**Exports**
Specific Gravity	0.75	0.76	0.75	0.76
Sulfur (PPM)	10	73	10	73
RVP (Kpa)	60	55	60	55
Olefin (vol%)	3.7	8.0	4.9	7.2
Aromatics (vol%)	34.8	30.8	33.2	31.2
Benzene (vol%)	0.9	0.6	0.9	1.3
Research Octane	95.0	90.7	95.7	90.7
Motor Octane	86.0	81.9	85.0	82.4

Source: Hart refinery model output

Table III.A.5: Gasoline Blend Composition: TAEE Cases

Volume Percent

	3% vol Ethanol as TAEE		5% vol Ethanol as TAEE	
Europe	**EU Gasoline**	**Exports**	**EU Gasoline**	**Exports**
Butane	6.2	5.5	6.2	5.2
Light Naphtha	4.4	2.2	8.6	7.6
Isomerate	16.0	0.0	16.2	0.0
Lt FCC Gaso	7.8	3.6	4.9	3.0
Hv FCC Gaso	4.0	41.8	2.8	40.8
Reformate	45.4	14.1	40.1	16.4
Alkylate	7.2	4.4	6.4	2.3
MTBE	0.0	7.3	0.0	7.3
TAEE	7.9	0.0	12.7	0.0
Ethanol	0.0	0.0	0.0	0.0
Other	1.2	21.1	2.1	17.3

Source: Hart refinery model output

Table III.A.6: Refinery Capacity Utilization: TAEE Cases

Million Tons/Year

		3% Ethanol as TAEE	5% Ethanol as TAEE
Europe	**Capacity**	**Utilization**	
Crude Distillation	848	677	674
Naphtha HDT	167	129	120
Isom (C5/C6)	25	16	16
Reforming	110	87	84
Kero/Distillate HDT	260	225	225
Heavy Oil HDT	71	65	65
Hydrocracking	74	68	68
FCC	130	117	117
FCC Naph. HDT	23	13	13
Alkylation/Polymerization	14	10	10
Coking	25	21	20
MTBE	2	2	2
TAME	0	0	0
TAEE	-	9	14

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

IV. CO_2 Impacts

A. 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 CO2 emissions.
- Lower oxygenate energy content will increase gasoline volume requirements, increasing gasoline CO2 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 CO2 emissions.
- Lower octane requirements will reduce gasoline reforming throughput. Additional refinery hydrogen will be required from on-purpose hydrogen generation, increasing CO2 emissions.

Table IV.1 summarizes refinery CO_2 emission impacts for the Ethanol and TAEE cases. Impacts are quantified for products or other refining activities where ethanol or TAEE 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 gasoline production between cases as discussed previously and indicated in tables IV.1.

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 cases as compared to the Base case.

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

In the TAEE cases, gasoline carbon content was reduced, while total gasoline volume increased to maintain constant gasoline energy supply but not as much as in the Ethanol cases. The result is a net decrease in gasoline CO_2 emissions.

The refinery fuel requirement is lower than the Base case in both the Ethanol and TAEE cases. The additional oxygenate volume and octane reduce refinery fuel needs. In both the Ethanol and TAEE cases, there is a net decrease in gasoline plus refinery CO_2 emissions versus the Base case.

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

Europe	2010 Base Case	3% Ethanol	5% Ethanol	3% Ethanol as TAEE	5% Ethanol as TAEE
Gasoline Consumption					
Thousand Tons/Year	102,240	103,190	103,980	102,930	103,570
Gasoline CO_2 Emissions					
Carbon Factor	0.866	0.859	0.853	0.858	0.85
Thousand Tons/Year	324,660	325,030	325,230	323,810	322,810
Refinery Fuel					
PJ/Year	1860	1850	1840	1850	1830
Thousand Tons/Year	127,020	126,380	126,130	126,310	125,240
Hydrogen Generation					
MMSCF/Year	11,406,400	1,152,300	1,141,000	1,122,700	1,151,200
Thousand Tons/Year	30,340	30,650	30,350	29,860	30,620
	482,020	482,060	481,710	479,980	478,670

Source: Hart refinery model output

B. CO2 Impacts of Merchant Component Production and Byproduct Variations

There are also potential CO_2 impacts outside the refinery. First, merchant MTBE 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.

Table IV.2 summarizes other (outside the refinery) CO_2 emission impacts for the Ethanol and TAEE cases. In all cases the reduction in merchant MTBE production yields a CO_2 emission reduction associated with merchant MTBE production and reduced methanol production (for merchant MTBE and TAME produced in the Base case).

For the 5%vol ethanol case, an additional CO_2 emission reduction is realized through changes in refinery by-product production. For the TAEE cases CO_2 emission reductions are also realized through changes in refinery by-product production, for both 3% and 5% ethanol. The by-product related reductions are greater for the 5% TAEE case than the 5% Ethanol case.

Table IV.2: Merchant Plant Fuel and Byproduct CO_2 Emissions: Ethanol and TAEE Cases

Europe	2010 Base Case	3% Ethanol	5% Ethanol	3% Ethanol as TAEE	5% Ethanol as TAEE
Process Fuel CO_2 Emissions					
CO_2 Thousand Tons/Year	190	60	60	60	60
Methanol Production					
CO_2 Thousand Tons/Year	390	230	230	230	230
By-Product Fuel Change					
CO_2 Thousand Tons/Year	1,430	1,430	1,330	1,280	1,230
	2,010	1,720	1,620	1,570	1,520

Source: Hart analysis

The net CO_2 emission impacts are summarized in table IV.3 for the Ethanol and TAEE cases. The emissions are broken down into the gasoline, refinery fuel, hydrogen production, merchant plant fuel and other byproduct fuel substitution impacts.

Table IV.3: Summary CO_2 Emissions: Ethanol Cases

Thousand Tons/Year

Europe	2010 Base Case	3% Ethanol	5% Ethanol	3% Ethanol as TAEE	5% Ethanol as TAEE
Gasoline Consumption	324,660	325,030	325,230	323,810	322,810
Refinery Fuel	127,020	126,380	126,130	126,310	0
Hydrogen Production	30,340	30,650	0	29,860	30,620
Merchant Plant Fuel	0	60	60	60	60
Methanol	390	230	230	230	230
Other CO_2 Impacts	1,430	1,430	1,330	1,280	1,230
Total	**483,840**	**483,780**	**452,980**	**481,550**	**354,950**
CO_2 versus Base Case		-250	-700	-2,480	-3,840

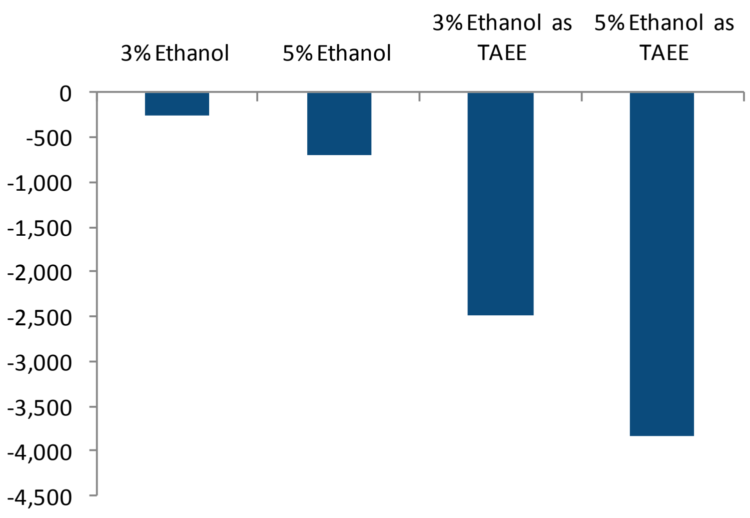
Source: Hart analysis and Hart refinery model output

With the total ethanol volume at 3%vol there is a small net reduction in calculated CO_2 emissions. The reduction increases threefold when ethanol is increased to 5%. With 3% TAEE the CO_2 reduction is an order of magnitude higher than when the ethanol is direct blended. There is an additional 1360 thousand tons per day reduction in CO_2 when the ethanol (feed to TAEE) is increased to 5%.

Figure IV.1 displays CO_2 impacts of Ethanol and TAEE cases relative to the Base case. The graph provides a comparison of ethanol vs. TAEE options. Again, CO_2 emission are reduced in all cases, but the reductions are significantly higher when the ethanol is converted to TAEE.

Figure IV.1: CO_2 Emissions vs. Base Case Ethanol and ETBE Cases

Thousand Tons/Year



Source: Hart analysis and Hart refinery model output

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) TAEE Energy – The source data for energy values does not include TAEE. TAEE energy was estimated from reported values for other similar 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):

$$\text{LHV (MJ/L)} = 39.347\ (\text{sg}) + 3.576$$

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.)

$$\text{LHV (MJ/L)} = 39.347\ (\text{sg}) + 3.576$$

Table A.1: Component Gravity and Combustion Energy

Gasoline/Component	Specific Gravity[1] (25°)	Combustion Energy[1]	
		MJ/L	MJ/kg
Ethanol	0.787	21.11	26.82
MTBE	0.735	25.85	35.17
ETBE	0.742[2]	26.93[3]	36.30[3]
Butane	0.573	26.20	45.73
Aromatics	0.863	35.28	40.85[3]
C_5 Ethers			
Ethyl Propyl Ether	-	-	35.4
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
TAME	0.7656	28.04[4]	36.62[4]
C_7 Ethers			
TAEE	0.7705[4]	28.43[4]	36.90[4]
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
[4] Supplied by CDTech

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.