

Well-to-Wheels Greenhouse Gas Emissions Analysis of High-Octane Fuels with Various Market Shares and Ethanol Blending Levels

Energy Systems Division

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by
Jeongwoo Han, Amgad Elgowainy, and Michael Wang
Energy Systems Division, Argonne National Laboratory

Vincent DiVita
Jacobs Consultancy Inc.

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Notation

AEO	Annual Energy Outlook
AKI	anti-knock index
API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BMEP	brake mean effective pressure
BOB	blendstock for oxygenate blending
BPD	barrel(s) per day
CAPP	Canadian Association of Petroleum Producers
CBOB	conventional gasoline blendstock for oxygenate blending
CG	conventional gasoline
CGF	corn gluten feed
CGM	corn gluten meal
CO ₂ -e	carbon dioxide equivalent
CRK	cracking refinery configuration (FCC, no coking)
DGS	distillers' grains with solubles
Dilbit	diluted bitumen
DVPE	dry vapor pressure equivalent
EIA	Energy Information Administration
FCC	fluid catalytic cracking
FFV	flexible fuel vehicle
FOE	fuel oil equivalent
FTP-75	federal test procedure
GGE	gasoline gallon equivalent
GHG	greenhouse gas
REET	Greenhouse gases, Regulated Emissions, and Energy in Transportation (model)
HCN	heavy catalytic naphtha
HHV	higher heating value
HOF	high-octane fuel
HOFV	high-octane fuel vehicle
HVYCOK	coking refinery processing heavy crude
HWFET	highway fuel economy test cycle
ICEV	internal combustion engine vehicle
LCN	light catalytic naphtha
LDV	light-duty vehicle
LHV	lower heating value
LP	linear programming

LPG	liquefied petroleum gas
LTCOK	coking refinery processing light crude
MBPD	thousand barrels per day
MCN	medium catalytic naphtha
MIT	Massachusetts Institute of Technology
MMBPD	million barrels per day
MON	motor octane number
MPG	mile(s) per gallon
MPGGE	mile(s) per gasoline gallon equivalent
MSAT	mobile source air toxics
MV	marginal value
NG	natural gas
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
ORNL	Oak Ridge National Laboratory
PADD	Petroleum Administration for Defense District
ppm	part(s) per million
psi	pound(s) per square inch (for gasoline vapor pressure)
RBOB	reformulated gasoline blendstock for oxygenate blending
RFG	reformulated gasoline
RFO	residual fuel oil
RON	research octane number
RVP	Reid vapor pressure
SCO	synthetic crude oil
T&D	transportation and distribution
ULSD	ultra-low-sulfur diesel
USGC	U.S. Gulf Coast
VGO	vacuum gas oil
WTW	well to wheels

Executive Summary

High-octane fuels (HOFs) such as mid-level ethanol blends can be leveraged to design vehicles with increased engine efficiency, but producing these fuels at refineries may be subject to energy efficiency penalties. It has been questioned whether, on a well-to-wheels (WTW) basis, the use of HOFs in the vehicles designed for HOF has net greenhouse gas (GHG) emission benefits. The objective of this study is to evaluate the impacts on WTW petroleum use and GHG emissions from (a) producing an HOF with a research octane number (RON) of 100, considering a range of ethanol blending levels (E10, E25, and E40), and (b) using these fuels to take advantage of vehicle efficiency gains. Three key factors determine the effects of HOFs on WTW GHG emissions: (1) changes in petroleum refining operations in order to produce HOFs, (2) GHG emissions associated with ethanol production, and (3) vehicle energy efficiency gains caused by HOF. We examine the changes in petroleum refining by using detailed linear programming (LP) modeling of various refinery configurations and HOF market penetration scenarios (3% to 71% of the total gasoline market). The HOF market penetration scenarios were developed by the National Renewable Energy Laboratory (NREL) using its ADOPT model. Based on results from other studies and inputs from Oak Ridge National Laboratory (ORNL) and NREL, a miles-per-gallon of gasoline-equivalent (MPGGE) fuel economy gain of 5% for HOF vehicles relative to the baseline regular gasoline vehicles (87 anti-knock index [AKI] E10 gasoline) was adopted, with a sensitivity case of 10% MPGGE gain for E40 blends (i.e., assuming volumetric fuel economy parity between E10 and E40). Because the HOF market shares depend on the fuel economies used in the ADOPT model, the same fuel economies for baseline regular gasoline vehicles used in the ADOPT simulation were employed in this WTW study. These factors were incorporated into the GREETTM (Greenhouse Gases, Regulated Emissions, and Energy in Transportation) model of Argonne National Laboratory to compare the WTW GHG emissions of HOF scenarios with those of the current baseline gasoline pathway using E10 gasoline with an AKI of 87 and approximately a RON of 92.

Figure ES1 illustrates the contribution of the ethanol blend, the 5% and 10% MPGGE gains, and the refinery changes to the overall GHG reductions of HOF vehicles. The overall WTW GHG emission changes associated with HOF vehicles were dominated by the positive impact associated with vehicle efficiency gains and ethanol blending levels, while the refining of gasoline blendstock for oxygenate blending (BOB) for various HOF blend levels (E10, E25, and E40) had a much smaller impact on WTW GHG emissions. The 5% and 10% MPGGE gains by HOF reduced the WTW GHG emissions by 4% and 8%, respectively, relative to baseline E10 gasoline. The additional WTW GHG reductions when corn ethanol was used for blending were 5% and 10% for E25 and E40, respectively. As a result, when corn ethanol was used, total WTW GHG emission reductions from using E10, E25, and E40 relative to baseline E10 gasoline were

5%, 10%, and 15%, respectively, with a 5% MPGGE gain, while using E40 achieved an 18% total WTW GHG emission reduction with a 10% MPGGE gain. When corn stover ethanol was used for blending, the additional WTW GHG reductions were 12% and 24% for E25 and E40, respectively. As a result, with the corn stover ethanol, total WTW GHG emission reductions from using E10, E25, and E40 relative to baseline E10 gasoline were 8%, 18%, and 28%, with a 5% MPGGE gain, while using E40 achieved a 32% total WTW GHG emission reduction, with a 10% MPGGE gain.

In addition to the impacts of vehicle efficiency gain, the blending level of ethanol, and the feedstock source of ethanol, the average WTW GHG emissions for the entire gasoline light duty vehicle (LDV) fleet depend on the relative market shares of HOF versus non-HOF. The fleet's average WTW GHG emissions are simply the weighted average of those for HOF and non-HOF vehicles. Thus, increasing the market share of HOFs that have more ethanol in the blend reduces the LDV fleet's average GHG emissions (in grams of carbon dioxide equivalent [g CO₂-e] per mile). As an example, Figure ES2 presents the relative fleet average WTW GHG emissions (in g CO₂-e per mile driven) for a gasoline vehicle fleet in Petroleum Administration for Defense District (PADD) 3 and a baseline non-HOF vehicle fleet. As the ethanol blending level and HOF market share increase, more ethanol penetrates the market. For Figure ES2, we capped the contribution of corn ethanol at 15 billion gallons per year and assumed that the additional ethanol demanded would be produced from cellulosic feedstock and that the fleet average fuel economies of baseline non-HOFVs (regular E10 gasoline vehicles) were at 23.9 MPGGE. Figure ES2 uses corn stover as an example of cellulosic feedstock. The figure shows that increasing the market share of E25 to 65% and of HOF E40 to 71%, along with a 5% MPGGE HOF vehicle efficiency gain, can reduce the average WTW GHG emissions of a gasoline LDV fleet by 10% and 17%, respectively. With a 10% MPGGE HOF vehicle efficiency gain for the E40 case, the reduction in a fleet's average WTW GHG emissions can reach 20% at 70% HOF market penetration. The corresponding fleet average WTW GHG reduction of E10 HOF is limited to 3% at a 25% HOF market penetration because of limited HOF market penetration with this low ethanol blending HOF. In particular, the LP modeling revealed that E10 HOF market penetration is feasible only up to approximately 25% when no refinery capital expansion is assumed. Results for PADD 2 are similar to those for PADD 3 and shown in the results section of this report.

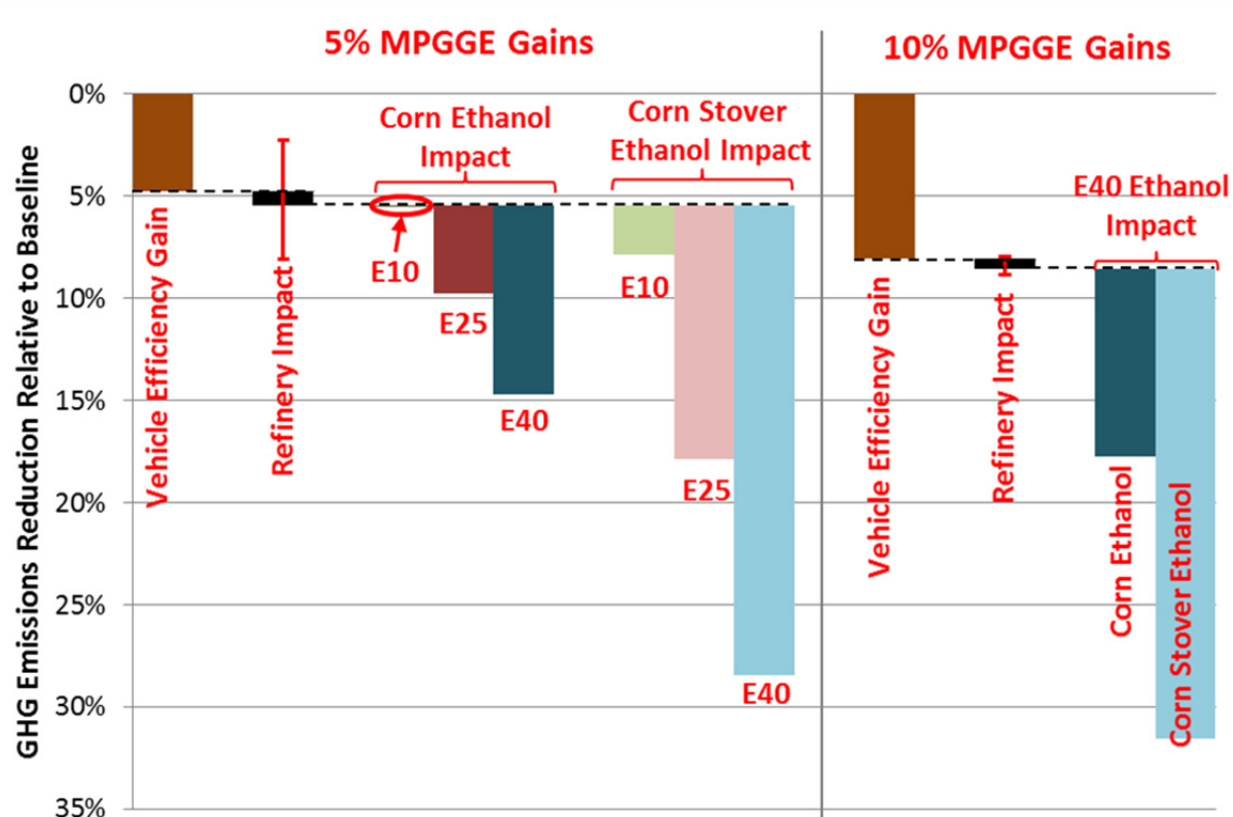


Figure ES1 HOF ethanol blend WTW GHG emissions reductions relative to regular gasoline (E10) in baseline vehicles

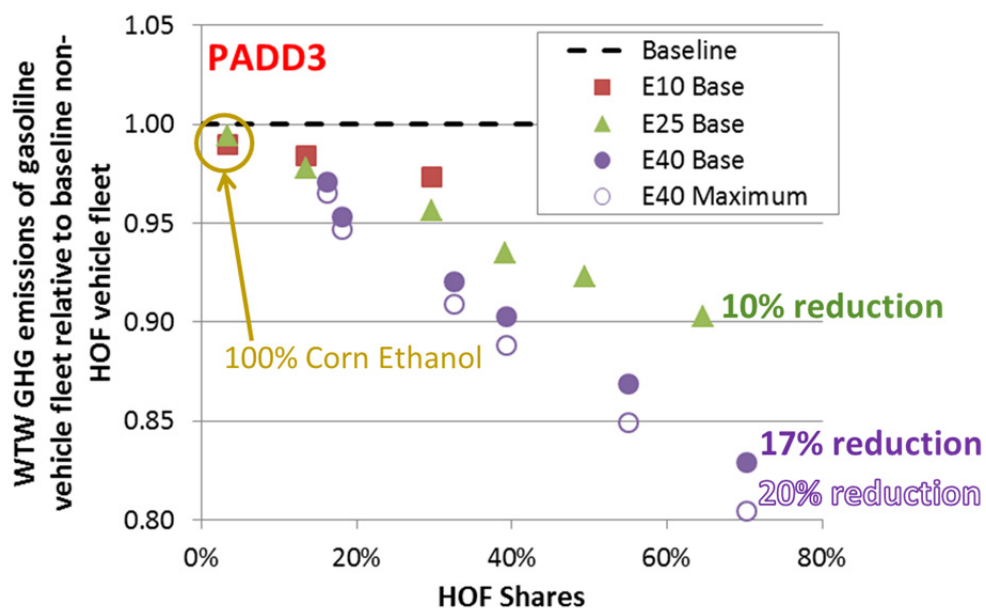


Figure ES2 WTW GHG emissions of gasoline vehicle fleet in PADD 3 relative to baseline non-HOF vehicle fleet on a per mile basis

1. Introduction

Increasing the gasoline octane rating can improve a vehicle engine's energy efficiency by allowing an increase in the engine compression ratio. Increasing the engine compression ratio from 10:1 to 12:1, with an appropriate change in gearing, can increase vehicle efficiency by 5–7%, and increasing the ratio to 13:1 can increase it by 6–9% (Hirshfeld et al., 2014; Leone et al., 2014). Depending on cylinder displacement and geometry and engine technology (e.g., direct injection, turbocharging, advanced spark control), each point increase in the compression ratio (e.g., from 10:1 to 11:1) requires a corresponding increase in the fuel's research octane number (RON) of 2.5 to 6 (Hirshfeld et al., 2014; Leone et al., 2014). Increasing the RON via ethanol blending provides an additional opportunity for increasing the compression ratio further due to ethanol's high latent heat of vaporization, which results in a reduced use of spark retard.

Producing high-octane fuel (HOF) requires changes in refinery operation, which may increase the energy and greenhouse gas (GHG) emission intensity of the gasoline product. A study by U.S. original equipment manufacturers (OEMs) examined the impact of increasing ethanol blending levels to produce an HOF with a different RON (Hirshfeld et al., 2014). The study showed that higher ethanol blending (E30) with 100 RON reduces the refinery/vehicle GHG emissions by 10% and petroleum consumption by 8% but increases the cost of producing HOF by 3-5¢/gal compared to regular gasoline with 93.2 RON. A Massachusetts Institute of Technology (MIT) study examined the impact of gradually increasing the HOF market share on carbon dioxide (CO₂) emissions and other social and economic costs (Speth et al., 2014). The MIT study was restricted to evaluating the current gasoline premium grade (98 RON) and ethanol blending levels of up to 20% by volume (E10, E15, and E20). The study showed that the increase in vehicle efficiency with HOF can offset the increase in refinery emissions. Speth et al. (2014) showed that gasoline with 98 RON could reduce annual U.S. gasoline consumption by 3.0–4.4%, while reducing net CO₂ emissions by 19–35 million tonnes per year (Mt/yr) in 2040, all at a cost savings. While the OEM study focused on various RON ratings with different ethanol blending levels, the MIT study focused on the increasing market share of the existing HOF premium grade. The focus of these studies was mainly on CO₂ emissions and the cost of producing HOF and the associated vehicle efficiency improvements. While the MIT study considered life-cycle CO₂ emissions at a high level of HOF penetration, the OEM study suggested that further well-to-wheels (WTW) life-cycle analysis of HOF gasoline in the United States is warranted.

Estimating the net change in GHG emissions associated with introducing HOF vehicles requires a WTW analysis of various gasoline HOF production options and vehicle efficiency gains. Such

an analysis should cover the major life cycle stages of HOF, including crude recovery (or crude oil production), transport and refining, ethanol production, and vehicle operation.

The objective of this study is to evaluate WTW GHG emissions and the petroleum use associated with the production and use of HOF (100 RON) gasoline, assuming a range of ethanol blending levels, HOF market shares, refinery crude slates, and vehicle efficiency gains. Such an evaluation requires a detailed assessment of HOF production impacts on refinery operations, by using a linear programming (LP) model, and a subsequent allocation of refinery emissions to various refined products. This study's allocation of emissions to products, including HOF, at the process-unit level is an improvement over previous studies, which examined total emissions at the aggregate refinery level. The energy and GHG emission intensity differences among the various HOF market shares and ethanol blending levels, together with data on the upstream production of crude types and ethanol options, were incorporated into Argonne National Laboratory's model named GREETTM (Greenhouse gases, Regulated Emissions, and Energy Use in Transportation) for a complete WTW evaluation of energy use and GHG emissions (Argonne National Laboratory, 2014).

This study consisted of three major tasks. In the first task, petroleum refinery modeling was employed to examine the impacts of producing 100 RON gasoline with three different ethanol blending levels (E10, E25, and E40) on the energy and GHG emission intensities of refining processes. A refinery LP model was used to simulate the production of gasoline blendstocks to satisfy various HOF market scenarios, while addressing RON, vapor pressure, and other requirements of final gasoline products. In particular, to examine the impacts of producing HOF at different market shares and various ethanol blending levels, Argonne collaborated with Jacobs Consultancy Inc., a company with extensive refinery LP modeling experience, to simulate refinery operations in a variety of existing configurations and with several ethanol blending levels to meet the octane rating of 100 RON.

In the second task of this study, impacts of crude types supplied to refineries were analyzed. Crude inputs to U.S. petroleum refineries are subject to significant changes in sources (hence their quality differs), depending on a variety of market factors. Argonne examined the impact of crude quality on overall refinery and product-specific efficiencies with LP modeling of 70% of existing U.S. refining capacity (Elgowainy et al., 2014). More recently, Argonne examined, in detail, the energy and GHG emission intensities associated with the various oil sands recovery and upgrading operations (Cai et al., 2015; Englander et al., 2015), since Canada is projected to increase its oil sands production from 1.95 million barrels per day (BPD) in 2013 to 4.81 million BPD by 2030 (CAPP, 2014). Most of the oil sands products (such as synthetic crude oil [SCO] and bitumen) have been exported to the U.S. market. For refinery LP modeling in this study, the

2020 projections of the mix of various crude types in different Petroleum Administration for Defense Districts (PADDs, see Figure 1) were taken from the U.S. Energy Information Administration's (EIA's) 2013 Annual Energy Outlook (AEO) (U.S. EIA, 2013).

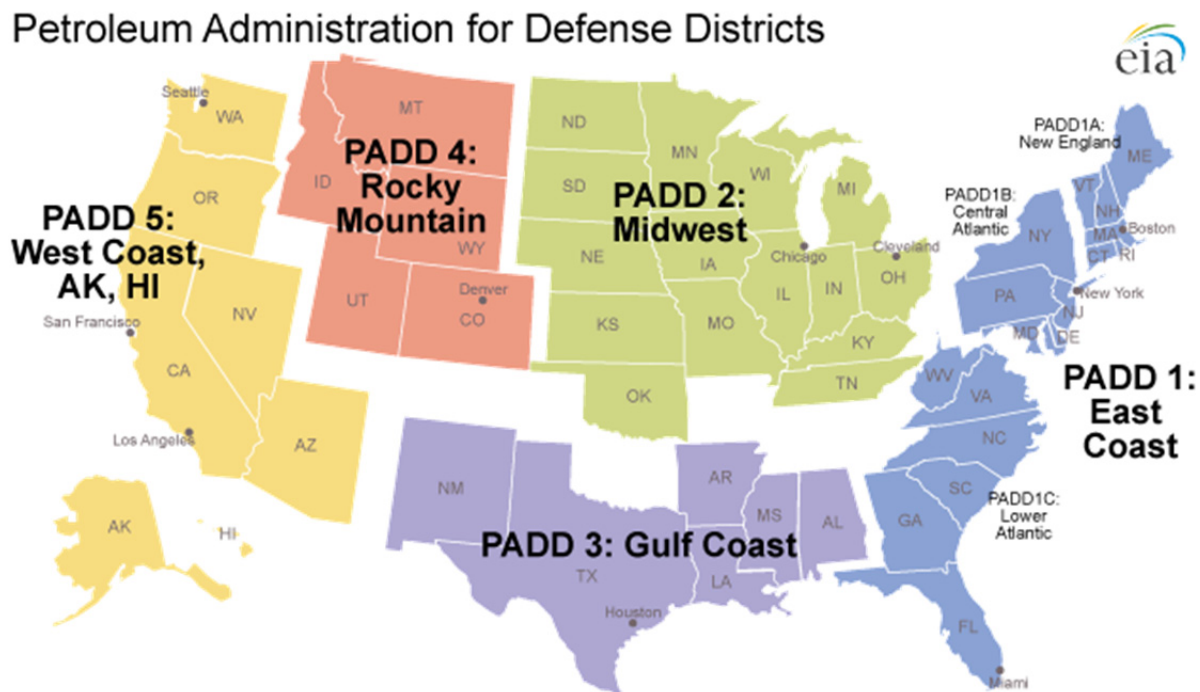


Figure 1 Petroleum Administration for Defense Districts (U.S. EIA, 2014a)

In the third task of this study, the GREET model was configured to incorporate results from the above two tasks and assessment of vehicle efficiency gains and to conduct WTW simulations of different HOF market scenarios and ethanol blending levels. The WTW analysis covered the impact of conventional and synthetic crude recovery (or crude oil production) and transportation to U.S. refineries, the refining of crude to produce HOF among other refined products, the transportation of gasoline blendstock to terminals for blending, the transportation of the final fuel product to refueling stations, and the combustion of fuel during vehicle operation. Since ethanol blending was examined as an option to produce HOF, the WTW simulations also covered the production of ethanol from corn and corn stover feedstocks, including the growth phase of the biomass, as well as transportation and the processes for converting biomass to ethanol.

2. Meeting HOF Specifications and the Role of Ethanol

Many fuel blending specifications must be met in order to produce finished gasoline, including sulfur, benzene, distillation, vapor pressure (measured as Reid vapor pressure or RVP), and octane specifications, to name a few. Two of the most critical of these are RVP and octane. In most blends, they are constraining specifications, meaning that these two specifications are achieved up to the specification point. For example, if the RVP should be less than or equal to 7 psi, the resulting RVP is rated at 7 psi.

2.1. Octane Rating of Fuels

The octane number of a fuel is a measure of its knock resistance when combusted under high compression in engines. Engine efficiency can be improved when the compression ratio is increased, but this requires the use of HOF to prevent knock, or uncontrolled auto-ignition of the end-gas. Higher-octane fuels have higher chemical activation energies (higher temperature threshold) for self-ignition under high compression. In general, branched hydrocarbons (isomers) and ring-structure hydrocarbons (aromatics) have higher octane ratings than do straight-chain alkanes (normal paraffins) (Ghosh et al., 2006).

Octane is an alkane hydrocarbon molecule with 8 carbon atoms and 18 hydrogen atoms (C_8H_{18}). It exists in several forms (iso-paraffins). Iso-octane in the form $3(CH_3)-C-C(H_2)-CH(CH_3)_2$ — also known as 2,2,4-trimethylpentane — serves as the standard (100 octane) on the octane rating scale. On the other hand, n-heptane, with the chemical formula $CH_3-5(CH_2)-CH_3$, has an octane number of 0. It should be noted that other fuels (such as hydrogen, methane, and butane) as well as several alcohols (such as methanol and ethanol) can surpass iso-octane's rating of 100 and thus have much higher knock resistance at high compression when used in internal combustion engines. Refiners blend hydrocarbon components with various octane numbers to attain the desired octane ratings of the different gasoline pools (e.g., regular and premium grades).

To determine the octane rating of a fuel component or a blend, several standard measurement methods can be used (ASTM, 2013a, 2013b; Kalghatgi, 2001). The research octane number method (RON – ASTM D2699) compares the performance of the fuel being studied in an engine, while changing its compression ratio, with the performance of a mixture of iso-octane (100 octane) and n-heptane (0 octane). The motor octane number (MON – ASTM D2699) method is conducted on the same engine but at a higher speed and with a higher intake air temperature than the RON test, using the same reference fuels. For test fuels, the MON is generally lower and intended to represent more aggressive motoring conditions than the RON. By definition, RON equals MON for iso-octane ($RON = MON = 100$) and for n heptane ($RON = MON = 0$). In the

United States, gasoline is currently sold on the basis of the anti-knock index (AKI), also referred to as road octane, which equals $(RON + MON)/2$ or simply $(R + M)/2$. Current conventional regular gasoline (CG) in the United States is 87 AKI and approximately 92 RON and 82 MON. The difference between RON and MON is called the “sensitivity,” and for many refinery gasoline streams, it is approximately 10 octane numbers. For modern boosted direct injection engines operating at low speed and high load, RON (testing at a lower speed) is a better predictor of knock performance than MON or AKI. Thus, the focus of this paper is set to meet the 100 RON HOF qualities, and we just focus on RON throughout.

2.2. RON and RVP Specifications

Gasoline blending in a refinery generally consists of a number of intermediate streams that are combined to achieve the target specifications. Each stream is produced in a different volume (quantity) and has unique blending qualities. Refinery operations can affect these quantities and qualities. For example, a reformer can operate across a severity range that spans from low to high. At high severity, the reformer produces a smaller volume of products with a higher octane and RVP. Thus, there is a trade-off: High octane is valuable, but both high RVP and smaller yields (i.e., volumes) are not desirable.

In most refinery operations, there is a cost associated with producing octane and lowering RVP. Key high-octane and low-RVP blendstocks are reformate and alkylate. Table 1 shows the ranges of “blending” RON and RVP values – the blending impact of an individual component quality on the finished gasoline quality – for typical refinery intermediate gasoline blendstocks. Reformate contains aromatics, so it can have a RON significantly above 100 at highly aromatic levels. However, high aromatic levels result in a lower volumetric yield, which cuts into a refinery’s profit margin. Alkylate is generally branched alkanes, so the RON of this stream will be less than 100 (unless it is all isooctane and triptane). Operationally, one production cost is associated with the liquid recovery percentage across a process unit. For example, in the reformer, which is the major producer of high-octane products in most refineries, the liquid reformate yield at low severity is approximately 90 volume percent (vol %) of the input feed, but that decreases to about 80 vol % at high severity. The “lost” liquid production appears in the higher production of light ends, which generally have less value than does reformate. For alkylate, there is shrinkage of about 20 vol % across the process unit.

Ethanol is another high-octane blending component (109 RON for neat ethanol). While the blending value of ethanol for RON is higher than most gasoline intermediate streams, its blending RVP is relatively high compared to that of some – but not all – gasoline intermediate streams (e.g., butane). Thus, while ethanol blending enhances the capability to achieve 100 RON HOF, it could cause meeting the gasoline RVP specification more challenging.

Production of 100 RON gasoline can be done by blending 91 RON BOB with 30 vol % ethanol (Anderson et al., 2012). According to several previous studies, use of 100 RON gasoline with mid-level ethanol in the blend can be leveraged to improve engine efficiency (as defined by fuel consumption for given loads) significantly (Anderson et al., 2012; Hirshfeld et al., 2014; Kalghatgi, 2001; Leone et al., 2014; Mittal and Heywood, 2009; Muñoz et al., 2005; Nakata et al., 2007; Speth et al., 2014; Stein et al., 2012). However, the inclusion of high volumes of ethanol in the gasoline pool represents a redistribution of intermediate gasoline blendstocks to achieve fuel specifications. In such cases, the refinery will make new gasoline blending recipes. This rebalancing will primarily focus on achieving the desired RON and RVP qualities in the gasoline pool. Introducing HOF with specifications that are different from those of the regular gasoline (e.g., RVP) could incur additional infrastructure costs, which were investigated in a HOF market adoption study by NREL (Johnson et al., 2015).

Predicting the final properties of a gasoline blend is complicated by the fact that blending of properties is not linear. Note that the blending value does not reflect average values of pure blendstock components. Moreover, ethanol has different blending impacts based on the concentration of ethanol in the gasoline blend. For example, the blending value of ethanol for RON to 100 RON HOF increases from 118 with E10 to 121 with E25 and E40 as shown in Table 1. The change in the blending value of ethanol for RVP is more noticeable than that for RON. Figure 2 shows the impact of blending ethanol with gasoline blendstock on the RVP of the blend. The highest RVP is observed at 19 psi when there is about 10 vol % ethanol in the blend (E10), which rapidly decreases with an increased ethanol concentration in the blend.

Another challenge in predicting the final properties of a gasoline blend is the wide range of quality of some streams as shown in Table 1; an example is reformate, for which changing the reformer severity can change the RON from approximately 90 to 101. Note that the severity also depends on a reforming unit. Cyclic reformers can achieve higher RON octane (100 – 101) than semi-regen types (97 – 98). In the USGC, the reported capacity of cyclic reformers is 70%. Thus, the higher octane reformer was chosen in this study. Fluid catalytic cracking (FCC) gasoline qualities are fairly narrow relative to some of the other streams. Many refiners can change the naphtha/kerosene cut point of the FCC distillation, which affects the volume and quality of the FCC naphtha. The heavy portion of the FCC gasoline is high in octane and low in RVP and can improve the quality of finished gasoline blending. Naphtha quality can vary based on crude distillation characteristics and can change significantly. Both isomerate and alkylate qualities can vary based on the type of isomerization or alkylation unit, as well as the quality of the feed to the process unit.

Table 1 Blending values of RON, AKI and RVP (psi) for various gasoline blendstock components

Blending Stream	Range		
	Octane		RVP
	RON	AKI	
Normal butane	92.5	90.3	59.0
Alkylate	90 – 96	89 – 95	4–6
Reformate	90 – 100	85 – 95	3–5
FCC gasoline	89 – 92	84 – 87	7–9
Isomerase	83 – 88	81 – 87	13–15
Naphtha	55 – 65	50 – 60	5–13
Ethanol to baseline gasoline	108 – 147	99 – 122	19.0
Ethanol to E10 HOF	118.0	N/A	19.0
Ethanol to E25 HOF	121.0	N/A	10.3/11.8
Ethanol to E40 HOF	121.0	N/A	9.0/11.8

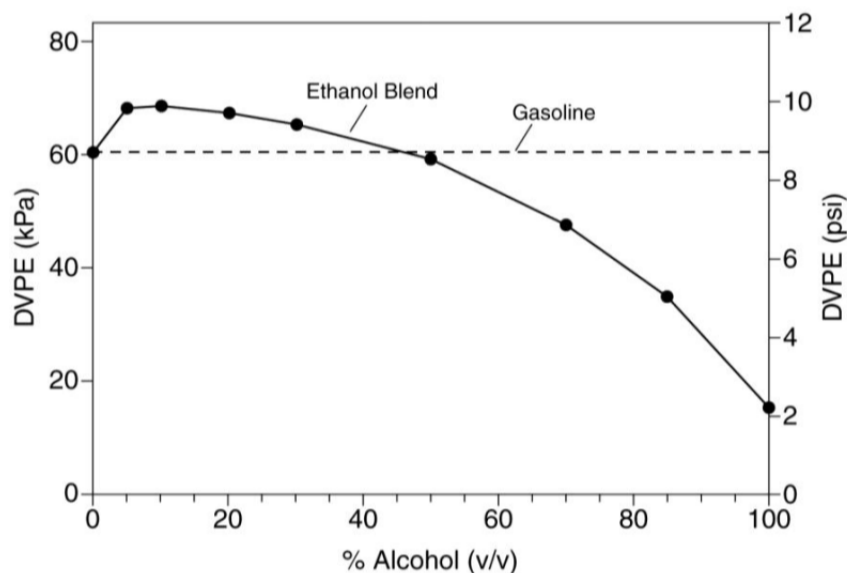


Figure 2 Impact of ethanol concentration in the blend of gasoline on the Reid vapor pressure (predicted dry vapor pressure equivalent [DVPE]) of the blend (Andersen et al., 2010)

There are multiple approaches for predicting the final quality of a gasoline blend. Many refiners use rigorous index and interaction coefficient methods for key specifications. This approach is very accurate within a narrow range of calibration specific to that refinery. In the modeling work, the qualities are blending values (as opposed to “neat” values), which represent the quality impact when a blendstock is volumetrically blended into the pool. In addition, the modeling implements tolerances. For example, the gasoline pool has blending tolerances of

approximately 0.1 for octane and RVP, meaning an 87.0 AKI specification must actually blend to an 87.1 AKI in the model.

For HOF, the RON and RVP are the two key fuel specifications to achieve. The RVP specification is seasonal, with a summer and a winter period, and it is more restrictive in summer. Table 2 presents the octane and summer RVP specifications of regular gasoline, premium gasoline, and HOF with E10, E25, and E40. While RON is used for the octane specification of HOF, the octane specification of regular and premium gasoline is set to be consistent with the current AKI specification of 87 and 93, respectively. 87 and 93 AKI roughly translates to 92 and 96 RON. For both regular and premium gasoline, the ethanol blending value for AKI is assumed at 113.4. It is important to note that a wide variation on reported ethanol octane blending value baseline E10 gasoline exists (99 – 122 for AKI and 108 – 147 for RON) depending on gasoline grade, season, and composition. The sensitivity of ethanol octane blending value is not investigated in this study.

In the United States, there are two sets of RVP specifications for each grade of conventional gasoline (CG) and reformulated gasoline (RFG), which is required in large U.S. cities that are in ozone nonattainment areas. The summer RVP standard is more stringent for RFG at approximately 7 psi (to maintain VOC compliance) than for CG. CG's summer RVP differs by PADD region. Two different PADDs were modeled in this study: PADD 3 (specifically, the Texas gulf coast) and PADD 2. CG's summer RVP for E10 (both regular and HOF) is set at 10 and 9 psi in PADDs 2 and 3, respectively, with a 1-psi waiver. The 1-psi waiver is not applied to HOF E25 and E40 because RVP decreases with 20% or more ethanol blending as compared to E10, as shown in Figure 2 (American Petroleum Institute, 2010; Andersen et al., 2010). Moreover, the

Table 2 Octane and summer RVP specifications of regular and premium gasoline and HOF with E10, E25, and E40

Octane and RVP	Regular (E10)	Premium (E10)	HOF E10	HOF E25	HOF E40
Gasoline octane	87 AKI	93 AKI	100 RON	100 RON	100 RON
BOB octane	84.1 AKI	90.7 AKI	98 RON	93 RON	86 RON
RFG in PADDs 2 and 3					
RFG summer RVP (psi)	7	7	N/A	7	7
RBOB summer RVP (psi)	5.6	5.6	N/A	5.7	5.1
CG in PADD 2					
CG summer RVP (psi)	10	10	10	9	9
CBOB summer RVP (psi)	8.9	8.9	8.9	8.4	8.8
CG in PADD 3					
CG summer RVP (psi)	9	9	9	8	8
CBOB summer RVP (psi)	7.8	7.8	7.8	7.0	6.8

impact of the 1-psi waiver was proven to be minimal at a higher ethanol blending level (Hirshfeld et al., 2014). In addition, a waiver for gasoline above E10 would require legislation, which is uncertain. In this study, CG and RFG shares in total gasoline are set to 75 vol % and 25 vol %, except for the E10 HOF cases. Note that a constant RVP standard is assumed for each PADD while RVP varies at the city, county and/or state level. Similarly, while some refiners have opted out of the waiver, we applied the waiver throughout each PADD.

This study assumes no additional capital investment, which potentially limits reformat and alkylate production, two valuable blendstocks with respect to octane and vapor pressure. The limited reformat production makes it significant challenging to produce a large volume of E10 HOF RFG due to RFG's tight RVP constraint in the summer. Additionally, the models were not allowed to sell high RVP, low octane streams such as naphtha, which would have eased these blending constraints. The impact of selling these poor quality streams can be investigated in future study. So, Producing E10 HOF RON 100 with RFG was demonstrated at low production levels (up to 8% HOF share). From 8% to 25% HOF share, the LP model was able to find feasible solutions, but further investigation showed that key operations were too stressful to be practical. The models are infeasible at 25% or higher. This centered at the inability to simultaneously maintain a high RON octane and balance RVP for all the grades of gasoline at the required ratios (percent RFG/CG and percent high/low octane). Thus, in order to show the impact of HOF at a notable penetration level, no RFG is assumed to be produced in the E10 HOF cases.

Ethanol blending responses to gasoline with respect to RVP also has a range of values, similar to octane. The ethanol blending RVP response appears to be somewhat wider than octane on a percentage basis. For this reason, a separate summer and winter RVP was used. For all E10 gasoline a blending RVP of 19.0 psi was assumed. For the scenarios on 100 RON, a unique RVP was used for summer and winter seasons, although the seasonal differences are relatively small. While these seasonal data for RVP are slightly higher in the winter, many gasoline blends are not constrained on RVP in the winter, rather other volatility specifications.

The LP model makes predictions for all blending qualities. Some qualities are assumed to be constant because there is only a small variation in blending value. Other qualities change based on refinery operations and constraints and the type of crude entering the system. There is an internal cost of production for blending components (both for gasoline and diesel blends). There are different blending recipes that would satisfy desired gasoline specifications, and the LP solution provides the optimal recipe that will maximize the overall profit margin with respect to the other refinery conditions and constraints.

2.3. Role of Ethanol in Producing HOF and the Role of BOB

Producing 100 RON HOF can be achieved via increased production of high RON blending components, such as reformate, alkylate, and isomerate. In addition to experiencing volumetric loss during their production, high-RON blending components are also energy intensive (Elgowainy et al., 2014), so producing more of them increases refining GHG emissions. Alternatively, 100 RON HOF can be produced by blending ethanol, with more ethanol in the blend accommodating lower-octane gasoline blendstock for oxygenate blending (BOB)

Given the challenges of transporting gasoline with ethanol, the refinery industry has adopted the practice of producing a semi-finished gasoline product (i.e. BOB) that is ready to be blended with the given amount of ethanol to produce a finished gasoline of the labeled grade. In this study, we use the term BOB for the refinery-derived gasoline blendstock that is required to make the final 100 RON HOF gasoline product at the respective ethanol content; therefore, E10 BOB is the blendstock required for making 100 HOF with 10% ethanol, etc. The selection of E10, E25, or E40 was determined on the following basis:

- The selection of E10 is consistent with the current blending level in regular gasoline.
- E25 was selected because the cost of an E25 dispenser is significantly less than the cost of an E26+ dispenser due to Underwriters Laboratories' listing protocols for dispensers (Moriarty et al., 2014).
- The selection of E40 offers refiners the opportunity to use low-cost BOB by blending with either refinery BOB and potentially some low-cost 70 RON natural gasoline or straight-run gasoline.

E40 also offers the potential for additional engine efficiency gain due to the ethanol's high latent heat of vaporization and its large share in the blend.

Figure 3 shows the RON of BOB for HOF (blue diamonds) depending on ethanol blending levels as well as the RON of BOB for regular gasoline (green triangle) and premium gasoline (red square). The RON of BOB in Figure 3 was estimated from the estimated RON for various gasoline and ethanol blends in Anderson et al. (2012). The RON numbers of regular and premium gasolines are roughly 92 and 96, respectively. As shown in Figure 3, the RON of BOB for E10 HOF needs to be 98, which is 4 to 5 octane numbers higher than current premium gasoline BOB (about 94). With 25% ethanol blending (E25 HOF), the BOB RON requirement goes down to 93, which is almost equivalent to BOB RON for premium gasoline. The RON of BOB for E40 HOF is even lower (86) than that of regular gasoline (about 89 for 87 AKI [equivalent to 92 RON] regular gasoline). Because multiple gasoline types exist in the market, the shares of

these gasoline types represent a key parameter in this study that affect the refinery operations and GHG emissions. This study uses the gasoline market share projections from the ADOPT model developed by NREL, which are discussed in Section 3 (Johnson et al., 2015). The ADOPT model provides the market shares of HOF and conventional gasoline (E10). In other words, the ADOPT model reports the aggregated share of regular, mid-grade, and premium gasoline. Since regular gasoline dominates conventional gasoline (over 84% in 2014) and HOF could penetrate the premium gasoline market, this study assumes the conventional gasoline share projected by the ADOPT model is the regular gasoline share. Thus, this study includes two types of gasoline: HOF (100 RON) and E10 regular gasoline (87 AKI). Depending on the market shares of HOF vehicles (HOFVs) and non-HOFVs, the shares of HOF and regular gasoline are thus determined.

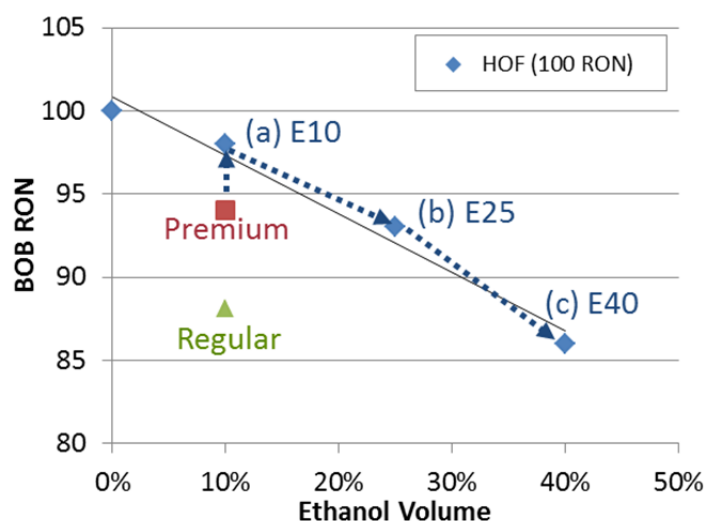


Figure 3 BOB RON versus ethanol volume share based on Anderson et al. (2012)

Depending on the relative cost spread between ethanol and other refinery high-RON blending components, certain ethanol blending levels may be more favorable with regard to the HOF production cost. Higher blending levels of ethanol relieve the refinery from the more intensive operations that would otherwise be needed to produce high-RON blending components. On the other hand, blending more ethanol for HOF production decreases its volumetric energy density, because the volumetric energy density of ethanol is approximately two-thirds of the corresponding energy density of alternative gasoline blend components. This study takes into account the disparity of the volumetric energy density in two ways. First, vehicle fuel economy is reported in miles per gasoline gallon equivalent (MPGGE), which is the miles per gallons corrected for the difference in energy intensity between a gallon of regular gasoline and a gallon of the product being evaluated. For example, E25 or E40 results in 5% or 10% energy loss per HOF gallon, respectively, when compared to E10. Note that increasing the ethanol blending level beyond E10 is more favorable for HOF RVP, as shown in Figure 2. Second, the volumetric amount of HOF production required in the LP runs is calculated from the energy amount of HOF

production (gasoline gallon equivalent, GGE) in the various scenarios to account for the differences in energy density and demand based on the improved vehicle efficiency. For example, the ADOPT model simulated the E40 case with 10% MPGGE gain. Thus, in order to meet the energy demand for HOFVs, this study increases the volumetric amount of HOF demands by adjusting the MPGGE gains downward by 4.8%. However, we acknowledge that an MPGGE gain by HOFVs that is lower than the 10% assumed in the ADOPT model could lower the market shares of HOFVs and HOF.

3. HOF Market Share Scenarios

The HOF market share is needed for petroleum refinery LP modeling, since high shares of HOF can push refineries beyond their existing limits and therefore be expensive to produce. In order to determine the market shares of HOFVs and non-HOFVs, the National Renewable Energy Laboratory (NREL) developed and analyzed eight HOF market penetration scenarios by using the ADOPT model (Johnson et al., 2015) and estimated the corresponding HOF market share for each scenario. Brief descriptions of these scenarios follow. The scenarios were developed by explicitly assuming that HOFs are to be produced with E25 and E40 ethanol blends.

- Scenario 1: Replacement of mid-grade fuel with HOF and conversion of premium-fuel vehicle models to HOFVs, then replacement of next-highest-performance models (E25 only)
- Scenario 2: Raising of octane floor (so RON is about 94 everywhere) and introduction of ethanol-tolerant, premium-optimized vehicles; this is intermediate step leading to HOFV market penetration (E25 only)
- Scenario 3: Price-driven adoption of HOFVs (with the most efficient vehicle models switched first) and the provision of station subsidies (with 40% and 80% of the incremental cost being used to upgrade to E25 and E40, respectively, for HOF) (E25 and E40)
- Scenario 4: Mandated deployment of HOF/HOFVs (applying to all vehicles starting in model year 2018 and the largest 20% of stations) (E25 and E40)
- Scenario 5: E85 becomes 51% ethanol (currently a legal fuel); use of flexible fuel vehicle (FFV) infrastructure; use of E51 as the backup fuel for HOFVs until HOF with ethanol blends is available (E40 only)
- Scenario 6: Requirement that all new dispensers be blender pumps (capable of pumping E40 HOF); price-driven adoption of vehicles (E40 only)
- Scenario 7: Regional deployment of ethanol blend HOF (e.g., Midwest, California), with buildup based on the existing FFV infrastructure (E25 and E40)
- Scenario 8: HOFVs become more expensive (new underground storage tanks and dispensers are needed so stations can dispense E40, a \$455 incremental cost for vehicles using HOF is assumed, and 20% of the largest gasoline stations must install a new tank and sell HOF by 2023) (E40 only)

Of the eight scenarios, we selected four (1, 3, 4, and 8; shown in Figure 4), which include the minimum and maximum HOF shares among all scenarios. Scenario 1 assumes mid-grade gasoline is replaced by HOF and new premium vehicle models are converted into HOF vehicles; this scenario is the minimum HOF market share scenario for HOF E25. Scenario 3 is a price-driven adoption scenario, which includes subsidies for vehicles and stations. Scenario 4 is an

accelerated deployment scenario, in which all vehicles starting with MY18 are HOF vehicles and the largest 20% of stations deliver HOF. Scenario 4 is the maximum HOF market share scenario for HOF E25 and E40. Scenario 8 is another price-driven scenario in which new underground storage tanks and dispensers for E40 are required and a \$455 incremental cost for HOF vehicles is assumed. Scenario 8 is the minimum HOF market share scenario for HOF E40. The ADOPT model generated the HOF market shares for the years from 2018 to 2050. Of these years, 2022 and 2030 were selected for refinery LP modeling of the four selected scenarios to examine the early and mature HOF market impacts in a discussion involving three national laboratories (Argonne, NREL, and Oak Ridge National Laboratory [ORNL]). Year 2022 is when the U.S. renewable fuel standard will set a maximum renewable fuel volume target. In 2030, Scenario 4 (the maximum HOF market share scenario) reaches a 70% HOF market share, and then it takes the next 20 years to achieve a 95% HOF market share. We acknowledge that this scenario is significantly aggressive and that other non-HOF technologies could limit the growth of HOFVs, depending on the competitiveness of those technologies. However, the maximum scenario is chosen to cover the entire range of estimated HOF market shares. On the other hand, Scenario 1 (the minimum HOF market share scenario) reaches only a 39% HOF market share in 2030. Thus, year 2030 provides a good range of potential HOF market shares.

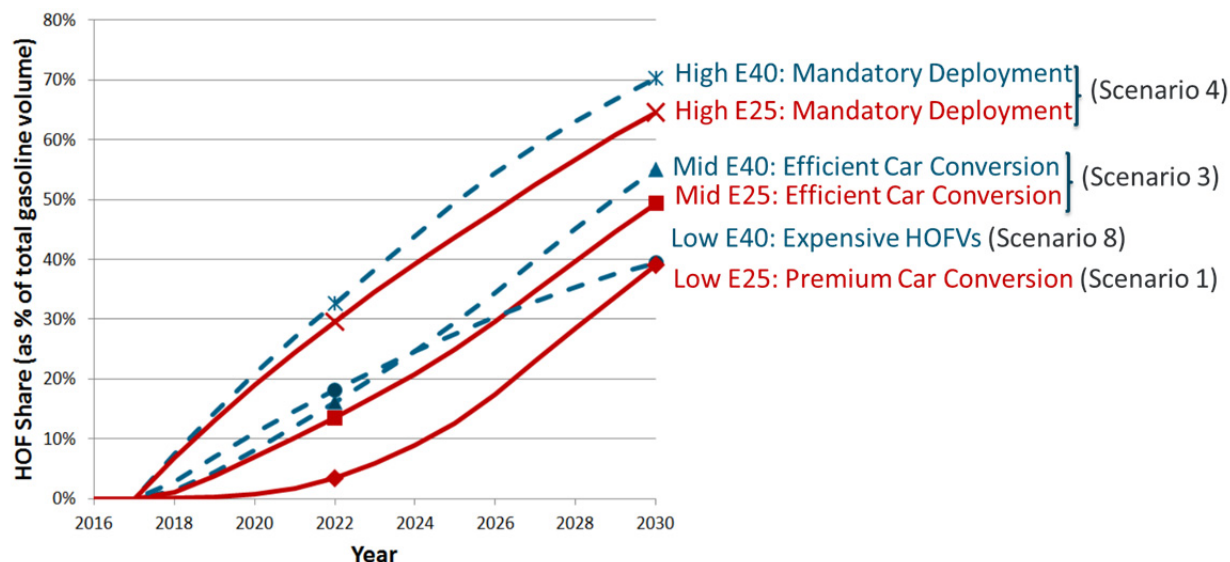


Figure 4 Selected HOF market penetration scenarios

Table 3 presents the HOF shares for the scenarios in the given years. Note that scenario 1 provides E25 HOF shares and scenario 8 provides E40 HOF shares, while scenarios 3 and 4 provide both E25 and E40 HOF shares. Also, the fuel shares for E10 HOF were not estimated. Instead, Argonne assumed them to be consistent with the HOF fuel shares for E25. In addition to 18 HOF market cases (3 HOF shares × 2 years × 3 ethanol blending levels), a baseline case

with 8% of premium E10 (93 AKI) and 92% of regular E10 (87 AKI) (representing the current market share of premium and regular gasoline) is examined.

Table 3 HOF market share scenarios for three ethanol blending levels in 2022 and 2030

Scenario	HOF	F.E. Gain (%)	Target Year	Gasoline Market Share (%)			
				Non-HOF E10	HOF E10	HOF E25	HOF E40
1 (Premium car conversion)	E10	5	2022	96.8	3.2	N/A	N/A
			2030	62.1	37.9	N/A	N/A
	E25	5	2022	96.6	N/A	3.4	N/A
			2030	60.9	N/A	39.1	N/A
3 (Efficient car conversion)	E10	5	2022	87.1	12.9	N/A	N/A
			2030	51.8	48.2	N/A	N/A
	E25	5	2022	86.5	N/A	13.5	N/A
			2030	50.6	N/A	49.4	N/A
	E40	5	2022	83.3	N/A	N/A	16.7
			2030	43.9	N/A	N/A	56.1
		10	2022	83.9	N/A	N/A	16.1
			2030	45.0	N/A	N/A	55.0
4 (Mandatory deployment)	E10	5	2022	71.4	28.6	N/A	N/A
			2030	36.5	63.5	N/A	N/A
	E25	5	2022	70.4	N/A	29.6	N/A
			2030	35.4	N/A	64.6	N/A
	E40	5	2022	66.4	N/A	N/A	33.6
			2030	28.6	N/A	N/A	71.4
		10	2022	67.4	N/A	N/A	32.6
			2030	29.6	N/A	N/A	70.4
8 (Expensive HOFVs)	E40	5	2022	81.2	N/A	N/A	18.8
			2030	59.5	N/A	N/A	40.5
		10	2022	81.9	N/A	N/A	18.1
			2030	60.6	N/A	N/A	39.4

N/A: Not available

4. Refinery LP Modeling Approach

There is much variation in the different refinery operations around the world. Some operations are designed to process heavy crude and are very complex in order to convert heavy crude into light products (liquefied petroleum gas [LPG], gasoline and diesel). Other refineries are less complex and tend to process lighter crudes in order to produce light products, yet their production of heavy products (fuel oil and bunker fuels) may be significant. One of the significant distinctions between refineries with high and low levels of complexity is their ability to convert the heavy portion of the crude into lighter products, which is often done in a delayed coking operation. The types and combinations of different operations in a refinery are often considered to make up the refinery's "configuration." One of the most common configurations in the United States is the coking configuration. This subcategory can be further subdivided into coking configurations that process very heavy crude down to those that process lighter crude. In addition, there are factors other than a refinery's configuration that affect the product distribution from a refinery. Some of these factors include the prices of feeds and products, the supply and quality of feeds (primarily crude), and market demands for products.

Refinery products such as gasoline are a mixture of intermediate streams of varying volume and quality blended to produce the desired amounts and target specifications. The volumes and qualities of these intermediate streams are a function of the configuration, type of feedstock, and operating conditions of the process units. Optimization of the refinery operations is a major challenge due to the multiple combinations of feedstocks, product requirements, and flexibility of the operating units, and the complex interactions among all of these factors.

In the refining industry, the most common tool for establishing the operating conditions is the LP model. The LP model represents the complex operations and interactions within the refinery. In a mathematical model, it calculates the production costs and associated revenues and provides a solution that maximizes (optimizes) the profit for a given set of inputs and constraints. The LP model establishes the operating conditions for the facility for maximum profit by using input feed and product prices, feedstock qualities, product-specification blending requirements, and unit operating conditions, among other factors. Outputs from the model include the overall margin and the estimated production, utility requirements (fuel gas, electricity, steam, and natural gas [NG]), product blending recipes, operational strategies, and a complete feed and product material balance for the system. Outputs from the LP models can also be used as inputs to exogenous models to perform energy balances.

Specific to the production of gasoline, there are many parameters for optimizing the refinery to meet octane specifications. The refinery has the flexibility to produce more or less of an

intermediate product, and the intermediate product can have a higher or lower octane number depending on the operation. For example, a refinery can reduce the reforming severity to produce lower-octane reformate for blending, and it can run an FCC unit at higher severity to produce a higher-octane FCC naphtha for blending. Each of these strategies has an associated cost (or savings). The LP model determines the optimal response for octane while taking all the other refinery operating parameters into consideration.

In this study, we use the LP model to predict refinery performance for different scenarios, because it represents what the industry will most likely do: look for the operations that will yield the maximum economic margin.

4.1. Representation of the U.S. Refining Industry in the LP Model

Representing the refinery industry in the LP model is always a challenge. At the extremes, a single model that represents the total industry can be built, or individual models for individual refineries can be built and then aggregated. The single model over-optimizes (assumes that all interactions lead to a perfect solution) and does not provide enough information about impacts on different refineries in the industry. The detailed agglomeration of individual refineries under-optimizes, since it cannot represent all the interactions between individual components that might yield synergistic solutions (all individuals see the same perfect market), and it is extremely difficult to develop and maintain.

One strategic approach to modeling is to aggregate all refinery configurations in a region (PADD) and develop an aggregate model. While this approach is commonly used, it lacks the granularity of analyzing a specific refinery configuration's responses to the HOF scenarios. In a configuration modeling approach, generic configurations are developed that represent the types of operations within the aggregate model. For this study, three generic refinery configurations were developed:

- Fluid catalytic cracking or FCC, no coking refinery: CRK,
- Coking refinery processing light crude: LTCOK, and
- Coking refinery processing heavy crude: HVYCOK.

All coking refinery configurations include an FCC unit. Each of the configurations represents a different set of crude feed, quantity and quality of intermediates, and operations. As such, each HOF scenario has different responses for each configuration compared to an aggregate model, which essentially simulates a single refinery response.

The refinery configuration model is developed as a typical fundamental configuration. Some refineries purchase and sell intermediate streams that could potentially affect operations but would be very specific to a location. For example, while it is well known that some refineries purchase FCC feeds or sell naphtha products, the configuration models intentionally do not adopt this structure because of the uncertainty of these strategies for specific locations. In addition, once a crude slate is established for a target scenario, it becomes fixed in the model for that scenario. Certainly, the change of crude affects refinery operations, but re-optimizing crudes with changing HOF market shares makes it challenging to isolate the impact of HOF production. The crude slate for this study was based on EIA AEO projections in 2020 for various regions.

Table 4 shows the configurations that were modeled for the study. Overall, there are six representations for PADD 3 (USGC) and PADD 2 (Midwest) regions with the CRK, LTCOK, and HVYCOK configurations. The PADD 3 model excludes inland refineries, which are small in terms of capacity. The capacity of the modeled operations represents about 70% of the total capacity in the United States. The dominant configuration in this study is the LTCOK. PADD 3 has a smaller percentage of CRK capacity (around 10%) than does PADD 2, which has about 31% CRK capacity.

Table 4 Refinery configurations and regions considered in this study

Region and Configuration	No. of Refineries	Capacity (MBPD)	Capacity (%)
PADD 3 CRK	7	740	10
PADD 3 LTCOK	17	5,300	71
PADD 3 HVYCOK	5	1,400	19
Total	29	7,440	100
PADD 2 CRK	11	1,120	31
PADD 2 LTCOK	8	1,670	46
PADD 2 HVYCOK	4	840	23
Total	23	3,630	100
PADD 2 + 3 CRK	18	1,860	17
PADD 2 + 3 LTCOK	25	6,970	63
PADD 2 + 3 HVYCOK	9	2,240	20
Total	52	11,070	100
U.S. crude runs in 2013 Capture		15,720	70

This study does not attempt to make a forecast of crude supply and demand for HOF market scenarios in 2022 and 2030. Many factors that are beyond the scope of this study influence such a forecast. The crude slate is instead grounded in EIA forecasts, and the models are not allowed to change the crude mix. For each of the modeled configurations, the crude slate was a combination of about four to five crudes that were deemed representative of the typical diet for each PADD/configuration combination. The crude American Petroleum Institute (API) gravity, sulfur, and vacuum residue quantities are shown in Table 5. Future work could include the HOF impact under different light and heavy crude availability scenarios.

The models are developed to produce “clean” fuels, with the following specifications:

- All diesel is ultra-low-sulfur diesel (ULSD) with 15 parts per million (ppm) sulfur content.
- All gasoline sulfur content conforms to the Tier 3 specification of 10 ppm sulfur.
- All gasoline benzene is compliant with the U.S. Environmental Protection Agency mobile source air toxics (MSAT) rules (0.62 vol %).
- RFG summer RVP is 7.0 psi for the E25 and E40 cases. No RFG is assumed for the E10 HOF cases.
- E10 RVP has a 1-psi waiver.
 - Summer: PADD 3 = 9.0 psi, and PADD 2 = 10.0 psi (includes waiver).
- E25 and E40 CG do not have the 1 psi RVP waiver.
 - Summer: PADD 3 = 8.0 psi, and PADD 2 = 9.0 psi.

Table 5 Crude quantity and quality for the different refinery configuration models and regions

Region and Configuration	Capacity (MBPD)	API Gravity (°)	Sulfur Content (wt %)	Vacuum Residue Yield (%)
PADD 3 CRK	740	42.4	0.4	8.1
PADD 3 LTCOK	5,300	30.9	2.0	20.6
PADD 3 HVYCOK	1,400	25.9	2.8	26.7
Total	7,440	31.2	2.0	20.1
PADD 2 CRK	1,120	39.5	0.4	9.9
PADD 2 LTCOK	1,670	29.8	1.8	19.5
PADD 2 HVYCOK	840	24.8	2.1	22.0
Total	3,630	31.3	1.5	17.2

The configuration models have the following additional representations that reflect typical refinery operations:

- Jet fuel production can range from 8% to 12% of crude.
- Premium gasoline production is limited to 10%.
- RFG production is set at 20% for coking configurations and 0% for cracking configurations, as described later.

The price sets for the configurations are based on the average of historical prices between 2011 and 2013. The prices are regionally developed for the USGC PADD 3 and Midwest PADD 2. Although representative crude prices are developed, they do not materially affect LP solutions since the slate is fixed. One significant price driver that affects model solutions is the spread between gasoline and diesel. For both regions, the average spot price for ULSD is about 20 cents per gallon higher than conventional gasoline, or 87 AKI (i.e., CG 87), which incentivizes diesel economics.

When HOF gasoline is produced, the same shares of RFG as those in the base case are assumed to be produced. Thus, for light and heavy coking configurations with 20% RFG volumes, the HOF scenarios must also produce 20% HOF RFG. For the cracking configuration, while some cracking refineries produce RFG, the amount of RFG produced from cracking refineries is limited because cracking configuration is only about 25% of the US capacity. Thus, we assumed that no RFG is produced from cracking configuration, as mentioned above. Regular gasoline in HOF scenarios is priced to be equal to the cost of CG 87, and HOF RFG is priced to be equal to the cost of conventional RFG. Ethanol is priced to be equal to the cost of conventional regular gasoline 87 AKI.

In the baseline models (non HOF gasoline), there are no volumes of export gasoline. For future HOF scenarios, export gasoline production is allowed for HOF scenarios. Once the base case production is determined, all future incremental gasoline production is limited to the base case. Export gasoline is specified as “typical” quality for Latin America (Mexico), with 30 ppm sulfur, 1.0% benzene, 35% aromatics, 12.5% olefins, 87 AKI, and a summer RVP of 8.0. When export gasoline is produced, the price is discounted when compared with the price of conventional gasoline. For PADD 3 and PADD 2, the discounts are 6 and 10 cents per gallon, respectively. The larger discount assumed for PADD 2 exports is meant to compensate for the longer transportation distance to U.S. ports. Note that this study is not an economic supply/demand analysis of the impacts of incremental gasoline on the world market. Prices are held constant throughout the study. EIA projected that U.S. gasoline demand is slightly reduced beyond 2020,

but the study holds the production at base case levels as an approximation. In future work, the impacts of gasoline prices and production volumes could be evaluated further.

All of the models are run seasonally to represent summer and winter operations (one representative day for each season). The key driver is the seasonal RVP change for gasoline and the cold flow quality change for ULSD. The seasonal approach is critical to understanding the HOF scenarios because of the more rigorous RVP summer gasoline blending specification.

The configuration models do not have rigorous capital investment options in the optimization process. The configurations are allowed to have spare capacity of approximately 3% for each unit, and the analysis is done to help users form opinions on investment requirements. More detailed capital investment options could be considered in future studies.

The HOF scenarios in Table 3 were used for refinery LP modeling. The HOF cases are initiated with a base case (0% HOF) using the conditions and operations described. The study includes two years (2022 and 2030), three ethanol blending volumes (E10, E25, and E40), and three levels of HOF shares: minimum (Min), middle (Mid), and maximum (Max).

For each case, the LP model is allowed to optimize the refinery system operation. Critical to the study is the optimization of intermediate-stream volumes and qualities blended into the various grades of gasoline. No constraints on blending recipes, other than the product specifications, are imposed on any grade, including export gasoline. In the model, there is operational flexibility in the process units so the critical volumes and qualities of the gasoline blending components can be changed. Some of the more robust alternatives include changing the endpoint on FCC naphtha and changing the throughput and severity of the reformer. The model has the ability to change butane purchases for all cases.

5. LP Modeling Results and Discussion

5.1. Refinery Response to Producing HOF

There are more than 100 refineries in the United States. The modeling basis for this study was generic configuration models (cracking, light coking, and heavy coking) for two PADD regions (PADD 2 and PADD 3). The results from these models reflect the approximate trends and responses in U.S. refineries. Any individual refinery will have a different response than the response of these configurations because each refinery has different feeds, process units, product slates, and blending considerations and constraints in the base-case operation. In spite of these differences, the results from these refinery configuration models are reasonably consistent with actual operations.

The significant variables affecting the modeling results are HOF market shares and HOF ethanol blending levels (E10, E25, and E40), as provided in Table 3. Results from the cases evaluated in this study can generate additional scenario cases; however, additional market scenario analysis is not the objective of this study. Rather, these results are representative of the underlying case assumptions and provide insight into typical responses in the U.S. refineries.

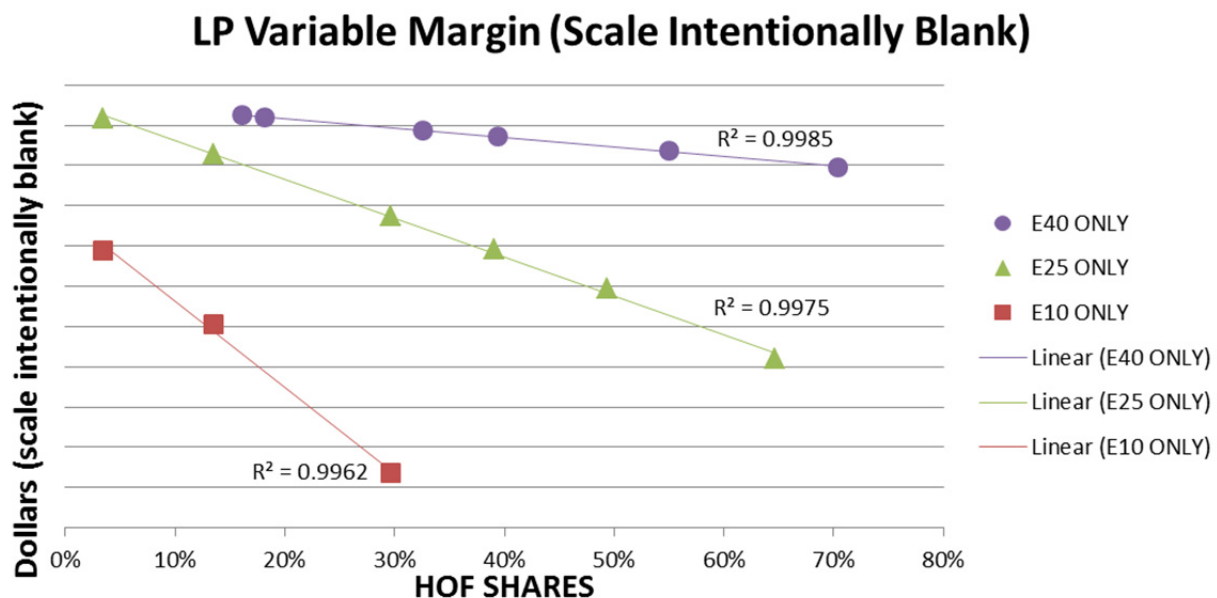


Figure 5 Impact of ethanol blending level and HOF market share on refinery profit margin based on LP modeling results

As background to LP models, when an LP run is initiated, there is a single mathematical goal: to maximize the objective value, which is the profit margin. The mathematical optimal solution is independent of any single event or operation. The LP model produces the highest (optimal)

profit within the constraints of the model. Figure 5 demonstrates this point by using actual LP results. The y axis is the objective value (expressed in dollars). The scale of this curve is intentionally blank. For all HOF scenarios, there is a consistent decline in margin, and the linear relationships are strong (as shown by the R^2 value).

There are few key observations that resulted from the analysis of HOF production. First, the E10 shares for the 2030 cases could not be modeled under the study assumptions and were not run. The reasons identified include the difficulty of increasing the RON by approximately nine numbers for each share of HOF while maintaining the RVP at specifications. This is described in more detail in the text that follows. Second, more often than not, the most significant challenge was finding a blend that achieves the RFG RVP specification of 7.0 in the summer. The modeling efforts showed extreme “stress” (often to the point of infeasibility) when producing this grade. In order to complete a series of cases with E10, the RFG RVP was modified to equal that of conventional gasoline, which includes the 1-psi waiver. In PADD 3 for example, the RFG RVP was changed from 7.0 psi to 9.0 psi (8.0-psi base plus 1.0-psi waiver).

The cracking configuration is typically more challenged to produce HOF. All individual refinery configurations are different, but generally speaking, the cracking configuration processes light crude, which has a higher volume of low-octane, high-vapor-pressure naphtha. The coking refinery tends to process heavier crude with a higher amount of vacuum gas oil (VGO), which feeds the FCC. Additional gas oil is produced by the coker, also to feed the FCC. This combination tends to provide a higher volume of FCC gasoline. FCC gasoline, while not as valuable as alkylate or reformate, is a relatively high-octane blendstock. Higher FCC feed will also produce more olefins, which can go to the alkylation unit. Alkylate is an excellent gasoline blendstock with a high octane number and low RVP. In broad terms, a more complex refinery has more operational flexibility to carry out “specification blending” than a less complex refinery has.

With regard to FCC operations, there is an operational change for most refineries. This involves the FCC gasoline production, which can be re-cut to different temperatures. For this example, the FCC naphtha is composed of light, medium, and heavy catalytic naphtha (LCN, MCN, and HCN, respectively). Refiners often “cut” the HCN into the diesel pool, which is especially true when there are strong diesel production economics. As shown in Table 6, HCN is approximately 16% of the full range, and it has the lowest RVP (0.1 psi, extremely low) and highest RON of all the cuts. These good blending qualities provide the flexibility needed to get higher-octane gasoline and reduce the RVP. The HCN (after additional processing) can typically be blended into either gasoline or diesel. However, this decision is an operational and economic one. Current and often forecasted prices favor strong diesel pricing relative to gasoline and would

favor routing the HCN to diesel. If the HCN stays in the gasoline pool for HOF production to maintain specifications as a consequence of a scenario, this could potentially be inconsistent with market economics to maximize diesel.

Table 6 Share of various naphtha grades from FCC process unit

Naphtha Type	Volume Percent	RVP	RON
LCN	48	12.8	92.6
MCN	36	2.6	90.6
HCN	16	0.1	93.3
LCN + MCN	84	8.4	91.8
Total (full range)	100	7.1	92.0

What follows is a generalized analysis for demonstration purposes to produce finished HOF gasoline under different cases, starting with an E10 basis. Table 7 illustrates that under regular E10 blending in Case 1, an 89.1 RON BOB is required to achieve 92.0 RON finished gasoline (about the same as the current RON). In order to achieve a 100 RON finished gasoline in Case 2, the BOB RON must increase from 89.1 to 98.0, an increase of about nine numbers. In order to maintain the finished gasoline pool RVP, the BOB RVP cannot increase. There are very few blend components that can meet this requirement. One candidate is reformate, which has high octane and low RVP. There are three limits, however: (1) the amount of naphtha feedstock to the reformer is limited, (2) there are limits on reforming throughput, and (3) there are operational limits on achieving high severity (some refiners might achieve 98 RON, while others might achieve 102 RON). Other high octane and low RVP blendstocks include iso-octene, iso-octane, and the other ethers, which are not currently in use in the U.S. These blendstocks, however, are not considered in this study for meeting RON specification. Another approach to control blending would be to remove low-octane, high-RVP blend components from the pool, such as light naphtha. There would be many variations on and cases for selling excess naphtha, and these were not explored in this study. The naphtha sales analysis is a function of market demands (domestic and export), the location of the refinery (inland, port), naphtha economics, and types of naphtha, just to name a few factors.

Table 7 Comparison of regular and HOF E10 specifications

Blendstock	Regular E10			100 RON E10 HOF		
	Case 1			Case 2		
	Volume Percent	Blend RVP	Blend RON	Volume Percent	Blend RVP	Blend RON
E10 BOB	90	7.9	89.1	90	7.9	98.0
Ethanol	10	19	118	10	19	118
Final blend	100	9.0	92.0	100	9.0	100

Additional HOF cases are presented in Table 8. Case 2 is from above for HOF E10 produced with 7.9 psi and 98.0 RON BOB. In Case 3, if the same finished gasoline specification is produced using E25, the required BOB RVP can increase to 8.3 and the BOB RON can decrease to 93; both these conditions are easier to achieve by the refinery. Note that the blending values for ethanol change from the E10 to the E25 blend. The last Case 4 removes the 1-psi waiver, which was in the E10 blend. In the study, only E10 blends had a 1-psi waiver. Compared with Case 2, Case 4 requires a more restrictive BOB RVP (going from 7.9 to 7.0 psi) and a reduction in octane requirement (going from 98 to 93 RON).

Table 8 Comparison of HOF E10 and E25 specifications

Blendstock	100 RON E10 HOF			100 RON E25 HOF			100 RON E25 HOF (No Waiver)		
	Case 2			Case 3			Case 4		
	Vol. %	Blend RVP	Blend RON	Vol. %	Blend RVP	Blend RON	Vol. %	Blend RVP	Blend RON
E25 BOB	90	7.9	98.0	75	8.3	93.0	75	7.0	93.0
Ethanol	10	19	118	25	11.1	121	25	11.1	121
Final blend	100	9.0	100	100	9.0	100	100	8.0	100

The cases just discussed are summarized in Table 9. In the final analysis, in order to produce HOF E10, with constant BOB RVP, the RON must increase by almost nine numbers. In order to produce HOF E25, the BOB RVP will decrease by about 0.9 psi, and the octane increase will be by about four numbers. Compared with E10, the E25 case will be easier to achieve for almost all refinery operations. The challenge of increasing octane by nine numbers is substantial, and that is why E10 for HOF RON100 will have extremely limited potential.

Table 9 BOB requirements for different HOF cases

Final Fuel	Case	Ethanol	Waiver	Blend RVP	Blend RON
Current (regular) 87 AKI (~92 RON)	1	E10	Yes	7.9	89.1
100 RON E10 HOF	2	E10	Yes	7.9	98.0
100 RON E25 HOF	3	E25	Yes	8.3	93.0
100 RON E25 HOF (no waiver)	4	E25	No	7.0	93.0
Delta (change)				RVP	RON
From current to HOF E10				0.0	8.9
From current to HOF E25 (no waiver)				-0.9	3.9

One of the modeling outputs from an LP model is marginal values (MVs) on limiting constraints. There are more sophisticated mathematical explanations for MVs, but they are not well suited for the context of this paper. In simple terms, if a refinery gasoline blend is constrained by the

RON spec, and the marginal value is \$0.42/Bbl, that can be interpreted as the cost of octane being \$0.42 per RON Bbl. If the octane MV increases in a future scenario, the interpretation is that octane became more constraining and it became more difficult (or costly) to achieve the specification. Since MVs change based on the season, configuration, grade of gasoline, prices of feeds and products, and many other factors, the appropriate analysis focuses on magnitude and direction, not absolute values for a single gasoline grade. On the basis of this background, Figure 6 shows representative octane cost for the cases. The delta octane cost reflects a delta to the base case.

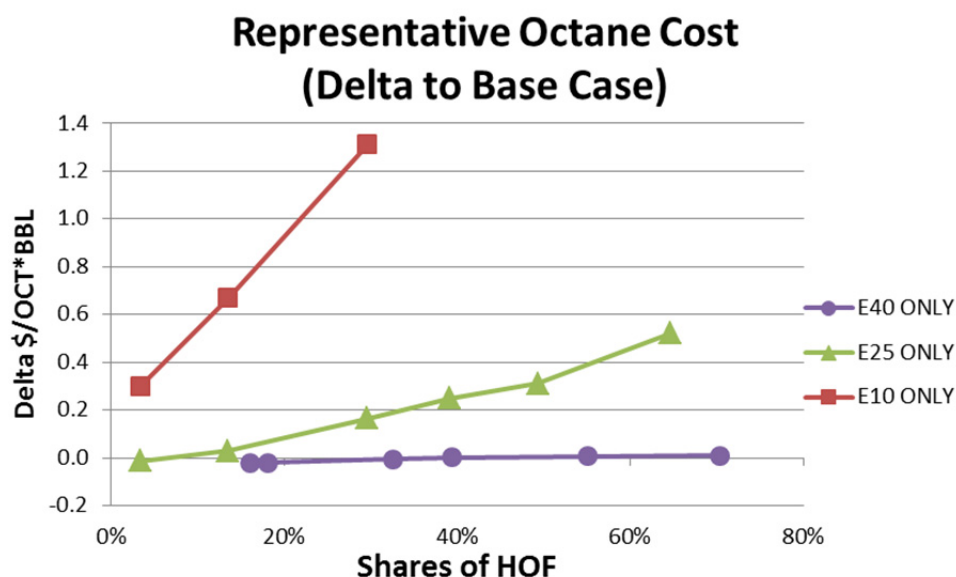


Figure 6 Impact of octane on refinery marginal cost for different ethanol blending levels and HOF market shares

This is an expected outcome (declining curve indicates more difficulty). E40 provides significant octane to the pool, and the ability to meet the octane specification is not challenged. The E10 response — the abrupt decline (steepness) of the curve — is significant. Note that the E10 cases had a looser RVP constraint, and the E10 case was run only for the 2022 cases. The results of any modeling effort cannot quantify actual refinery responses across all of the U.S. system of more than 100 refineries, but under the conditions and constraints of this study, it appears that producing any meaningful volume of 100 RON E10 HOF gasoline in the United States will be significantly challenging.

A similar curve can be generated for RVP to show the representative responses for various HOF shares (Figure 7). This also would be representative as a delta from the base case. The trend of the RVP response is expected. The E10 is extremely challenging with respect to RVP, in part because of the high RVP blending value for ethanol for E10. This RVP response plus the octane

response above provides additional confirmation of the challenges associated with HOF production using E10. The E25 and E40 curves are similar up to about 40% HOF shares. Above this level, E25 shows more difficulty in managing RVP than E40, which accounts for approximately the same share where the E25 and E40 octane incentives diverge (see Table 9). As the E25 octane pool becomes more challenged at higher HOF shares there is a relatively steep reduction in butane blending compared to the E40 response. These decreases indicate more challenging RVP blending because butane has a high RVP quality.

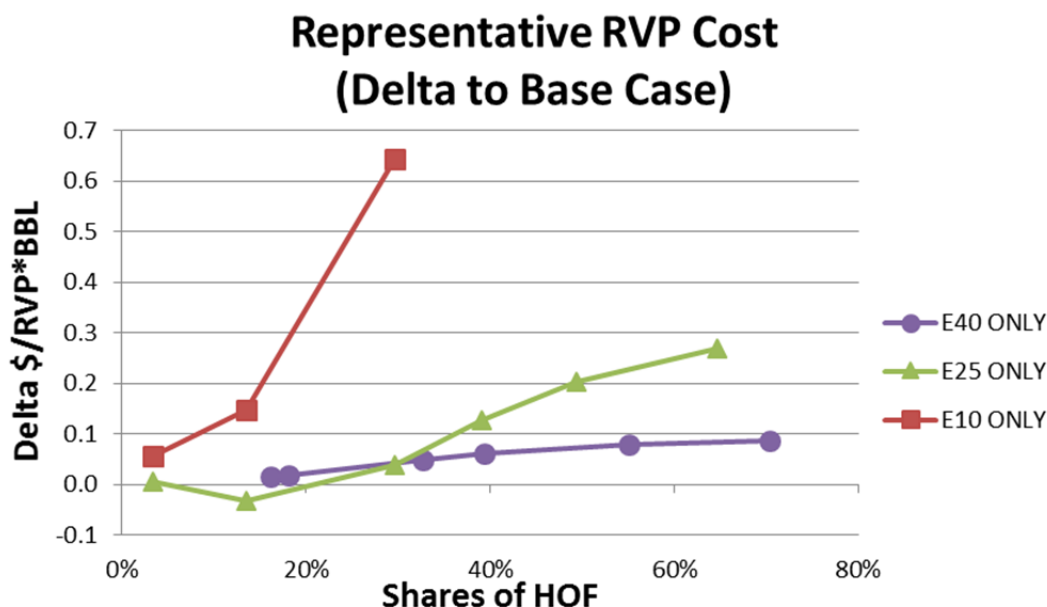


Figure 7 Impact of marginal cost on RVP for different ethanol blending levels and HOF market shares

With respect to this study, the specifications of concern are RON and RVP. Marginal values of RON and RVP cannot be compared to interpret if one quality is more difficult to achieve than the other, because there is no common denominator to differentiate the costs in \$/RVP versus \$/RON.

In addition to interpreting marginal values, a similar analysis can address the value of intermediate blendstocks (Figure 8). The values of a blendstock can change among cases, configurations, grades of gasoline, and feedstock and product pricing, for example. Nonetheless, this analysis can be beneficial in helping one understand the HOF responses.

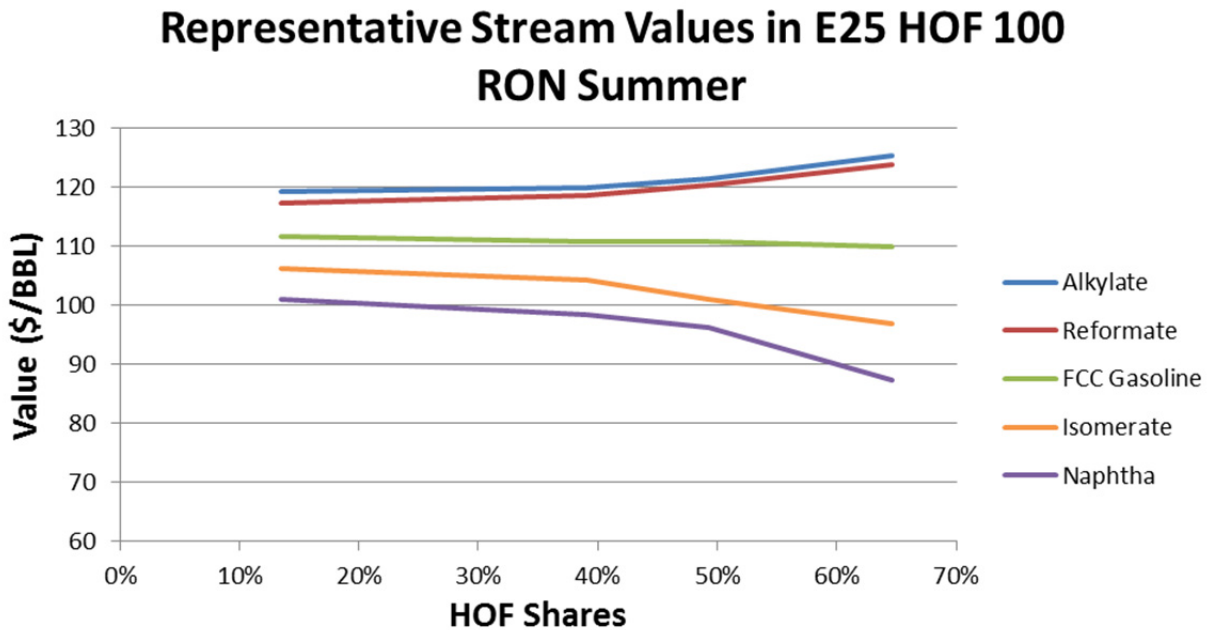


Figure 8 Representative stream values for 100 RON E25 HOF in the summer

Butane and ethanol values are not shown because these streams are purchased, not produced, and the value is simply equal to the purchase price. The reformate and alkylate streams (high octane, low RVP) have increasing value compared to the gasoline blend pool because of the increasing challenge to balance both RVP and octane as more HOF shares are produced in the E25 cases. Similarly, low-octane, high-RVP naphtha and isomate decline in value with incremental HOF shares. The value of FCC naphtha, whose quality approximates that of the total gasoline pool, remains flat. Analysis of these data suggests a strong correlation between RVP, octane, and stream value. In general, the refinery is more challenged to balance the RVP versus octane at higher shares of HOF.

The reforming operations unit is a critical process unit affected by HOF. A refiner can run higher or lower throughputs to the reformer and can also change the severity of the unit. In general terms, severity is directly related to product octane. The liquid reformate has an associated RON value, which is roughly equal to the severity. A severity value of 95 produces reformate with approximately 95 RON; in other words, the terms “reformer severity” and “reformate RON” are often used interchangeably. Although severity increases the reformate octane, there is a downside too: less liquid yield. Also, higher severity will increase the RVP, albeit by a relatively small amount.

Figure 9 is a chart of the change in the average refinery C3+ yield followed by reformer severity relative to the baseline case. These are deltas from the base case. Because E40 provides high

octane from ethanol, the severity curve is relatively flat, and there is a noticeable improvement for liquid recovery (see Figure 10). Higher liquid recovery benefits operations. The E10 severity delta goes to the maximum severity and is flat because there are operational limits preventing higher severity. Note that the change in liquid yield on the y-axis is a very small percentage of the overall liquid production; however a small 1% liquid yield change is significant and an important metric for refinery operations. Any decline in liquid yield most likely has a negative impact on the refinery margin.

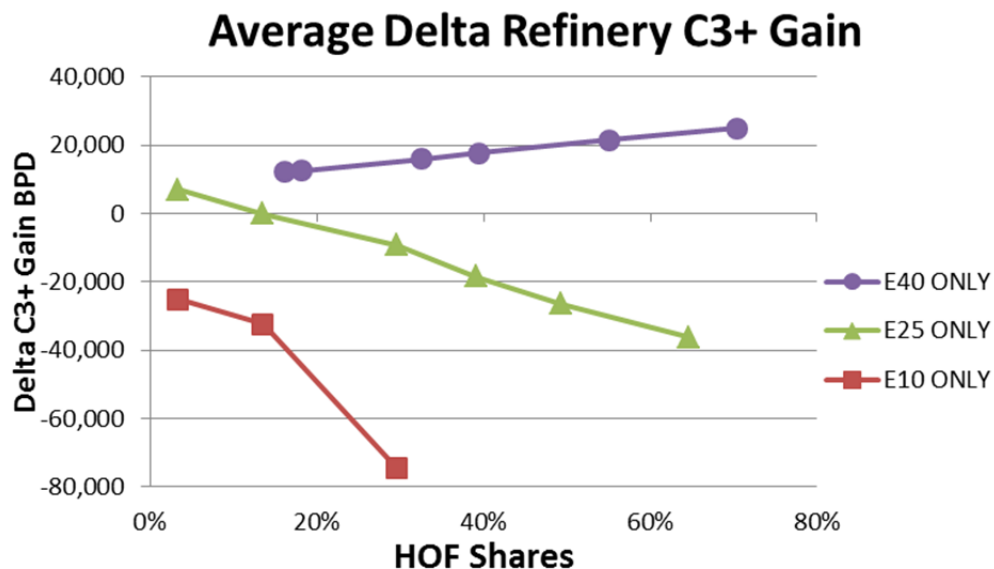


Figure 9 Changes in desirable products (C3+) yield from a reformer with ethanol blending level and HOF market share

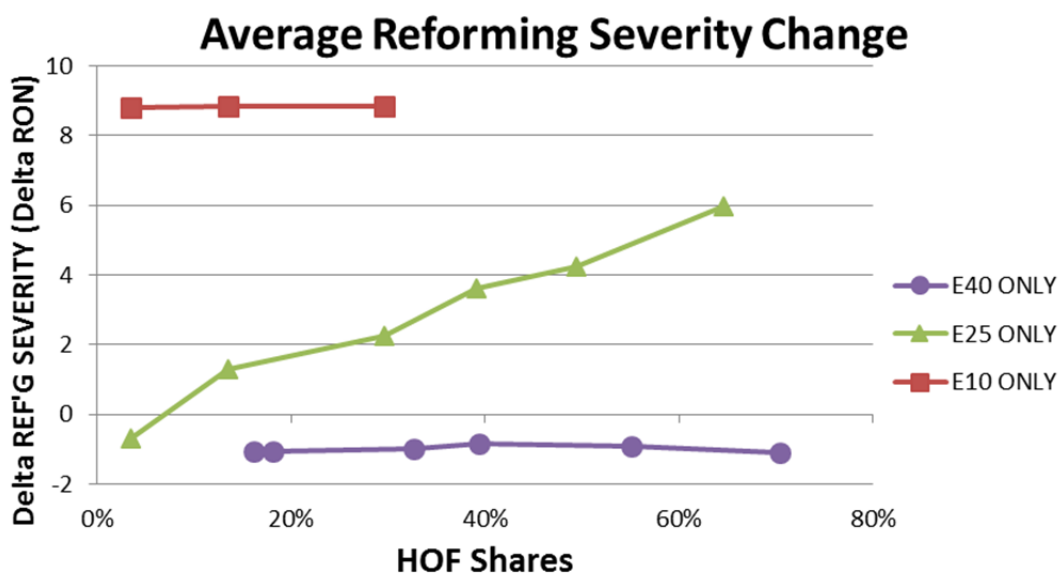


Figure 10 Changes in reformer severity with ethanol blending level and HOF market share

Another noteworthy impact associated with HOF gasoline is butane purchases. Changes in butane purchases provide insight into RVP control. Butane is a good octane source, but comes with an extremely high RVP trade-off. A significant decrease in butane purchases indicates a greater RVP blending challenge. Figure 11 shows that the slope for reduction in butane purchases is steeper for E10 than for E25 and E40. This emphasizes that butane blending can be an operational change for HOF gasoline production. For E40 gasoline, the ethanol dramatically increases the octane pool, reducing the need for butane that is high in RVP. Note that butane is generally one of the least expensive gasoline blendstocks, so any decrease in butane blending will likely negatively impact margin.

The basis of this study was to allow the export of gasoline after the desired base-case production was met. It follows that higher-ethanol blendstocks will result in higher exports of gasoline. Figure 12 shows the delta ethanol purchases for finished gasoline, and Figure 13 shows the volume of export gasoline. The export gasoline had no oxygenate. At high HOF shares, E40 gasoline exceeds 1 million BPD for ethanol consumption and gasoline exports above the current base case, which reflects a substantial volume increase. The impacts on export gasoline volumes can be the subject of further study.

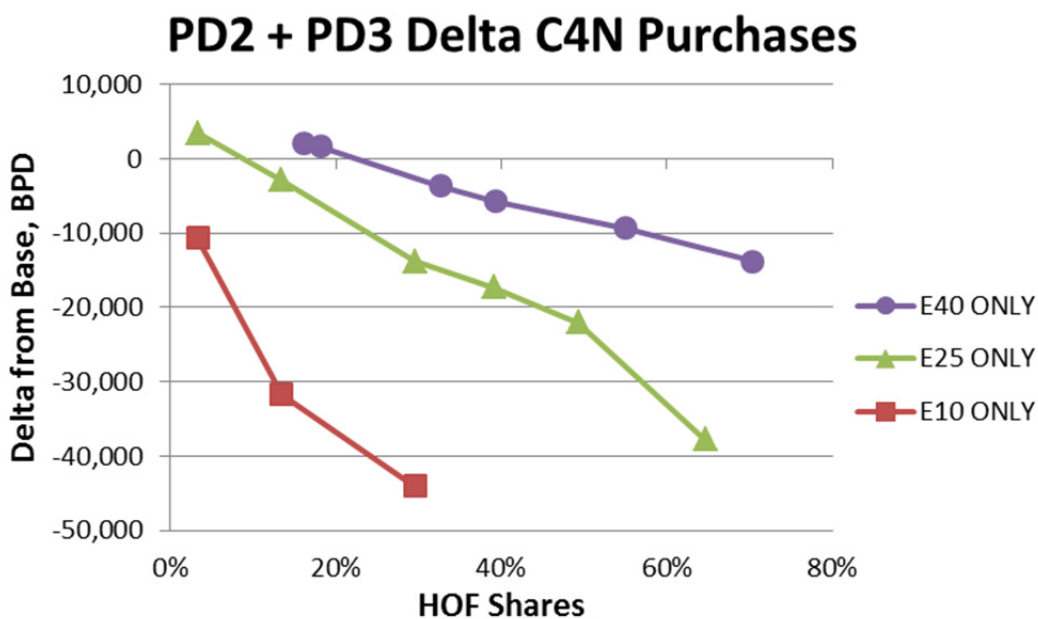


Figure 11 Changes in butane purchase with ethanol blending level and HOF market share

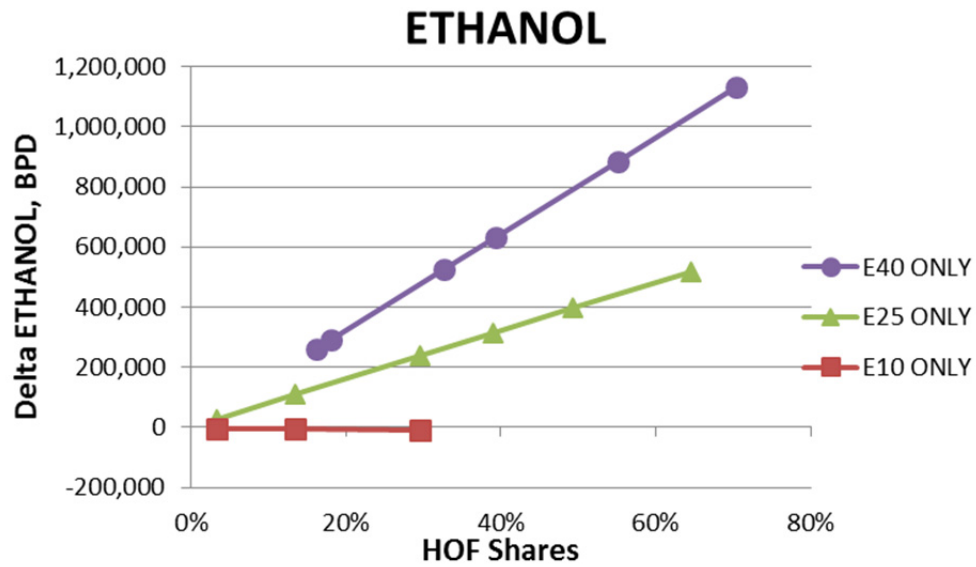


Figure 12 Changes in ethanol demand with ethanol blending level and HOF market share

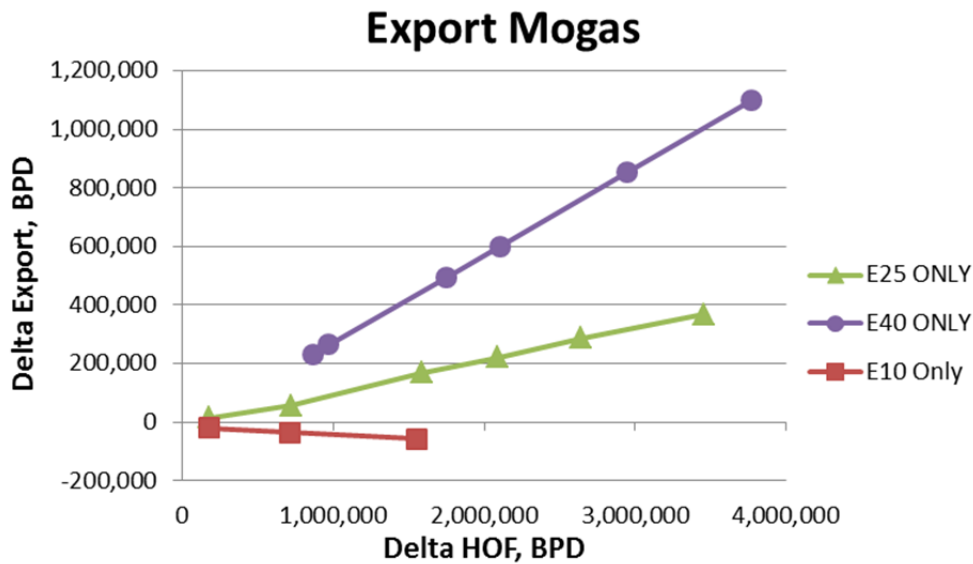


Figure 13 Changes in gasoline export with ethanol blending level and HOF market share

5.2. Overall Refinery Energy Efficiency

The overall refinery energy efficiency is defined as the total energy outputs in refining products (e.g., gasoline, jet fuel, diesel, LPG, residual fuel oil [RFO], pet coke, etc.) divided by the total energy inputs (e.g., crude oil, butane, natural gas, hydrogen, electricity, other feedstock, etc.) as shown in Equation (1). However, ethanol volumes for blending into gasoline BOB are not counted in the refinery energy inputs or outputs.

$$\eta_{LHV} = \frac{\sum_n (P_n \times LHV_n)}{\sum_m (C_m \times LHV_m) + \sum_o (OI_o \times LHV_o) + NG_{purchased, LHV} + H_{2, purchased, LHV} + Electricity_{purchased}} \quad (1)$$

where:

η_{LHV} is the LHV-based overall efficiency of a refinery;

P_n is the amount of refining product n (e.g., gasoline, jet fuel, diesel, LPG, and residual fuel oil [RFO]) in barrels;

C_m is the amount of crude input m in barrels;

OI_o is the amount of other input material o (e.g., butane) in barrels;

$NG_{purchased, LHV}$ is the LHV-based energy of purchased NG (in the case of purchased steam, it is combined with NG, and a boiler efficiency of 80% is assumed);

$H_{2, purchased, LHV}$ is the LHV-based energy of purchased hydrogen;

$Electricity_{purchased}$ is the energy in purchased electricity; and

LHV_m , LHV_n , and LHV_o are the LHVs of crude input m , refining product n , and other input material o , respectively, in million Btu per barrel.

For the energy efficiency calculation, energy balance results are needed. These can be calculated from the volumetric and mass input and output results from the LP model using the lower heating values (LHVs) of products. For solid products (e.g., delayed coke), GREET's default LHVs are used. The LHVs of gaseous products (H_2 , CH_4 , butane, etc.) are obtained from Green and Perry (2007). The LHVs of liquid products are estimated from the higher heating values (HHVs) that are calculated by using the following regression formula from API Basic Petro Data (API, 2014):

$$\text{HHV (Btu/lb)} = 17,672 + 66.6 \text{ API} - 0.316 \text{ API}^2 - 0.0014 \text{ API}^3 \quad (2)$$

where API is the API gravity of products, calculated as $141.5/(\text{specific gravity}) - 131.5$. The specific gravity of products, or the ratio of their density to water density, is calculated from the volumetric and mass flow rates provided by the LP model. HHVs are converted into LHV by multiplying them by 0.94, the average ratio of LHVs to HHVs of liquid petroleum products in GREET. Other utility consumptions (e.g., electricity and steam) are provided from the LP model.

The LP models were run for one representative day in summer and winter. Figure 14 presents the overall refining energy efficiency versus HOF shares in PADDs 2 and 3, averaging the two days (one in summer and one in winter) and the three refinery configurations (cracking, light coking and heavy coking). The overall refining efficiency is the weighted average of the refining energy efficiencies of the three configurations described above (cracking, light coking, and heavy coking) by their production volumes (see Table 4). In both PADDs, the overall refining efficiencies are fairly unchanged with changes in the ethanol blending levels and HOF shares. PADD 2 refineries have slightly higher overall refining efficiencies than PADD 3 refineries because of the higher refinery complexity and lower crude quality in PADD 3 (see Table 5). The results are consistent with the results in Forman et al. (2014). Note that PADD 2 receives a large share of Canadian oil sand in the form of synthetic crude oil (SCO), which has gone through intensive hydrocracking before entering refinery gates. The energy and emissions burdens of this upstream hydrocracking are taken into account for WTW analysis (Cai et al., 2015; Englander et al., 2015).

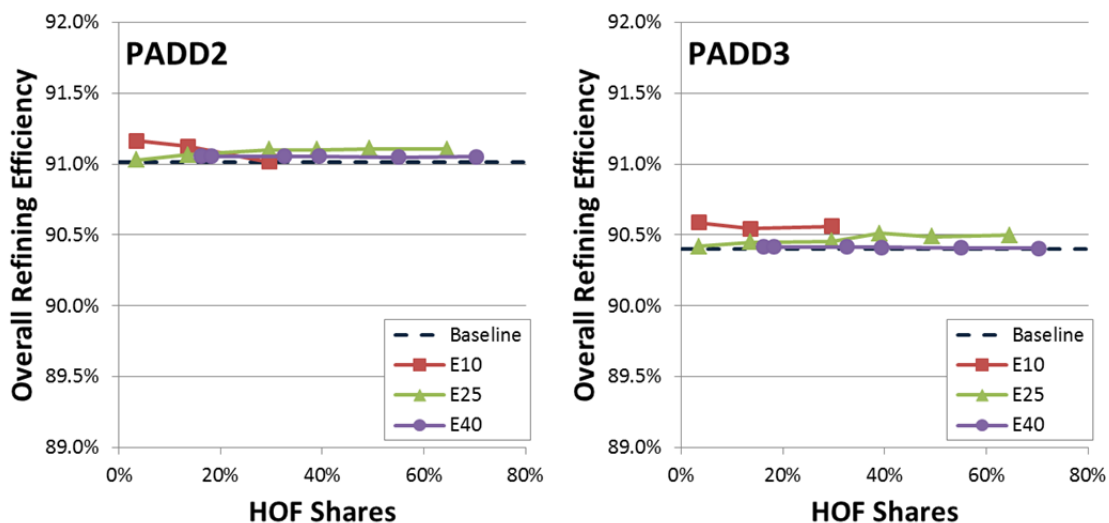


Figure 14 Overall refining efficiency versus HOF shares for PADDs 2 and 3

Figure 15 presents the annual average overall refining efficiency versus HOF shares for each refinery configuration in PADD 3, averaging two representative seasonal days (one in summer and one in winter). The overall refining efficiencies of each configuration are fairly consistent with changes in the ethanol blending levels and HOF shares. As the refinery becomes more complex from cracking to heavy coking, the overall refining efficiency decreases significantly. The decreases in the overall refining efficiency result from heavier crude inputs and higher refinery complexity, as investigated in Elgowainy et al. (2014). The drop in overall refining efficiency is larger with greater refinery complexity (e.g., light coking relative to cracking, and heavy coking relative to light coking). Similar trends were also observed in PADD 2 refineries. The small increase observed in the refining efficiency for the HOF E10 case is a result of more fuel gas and hydrogen production from the reformer that produces high RON reformate. The

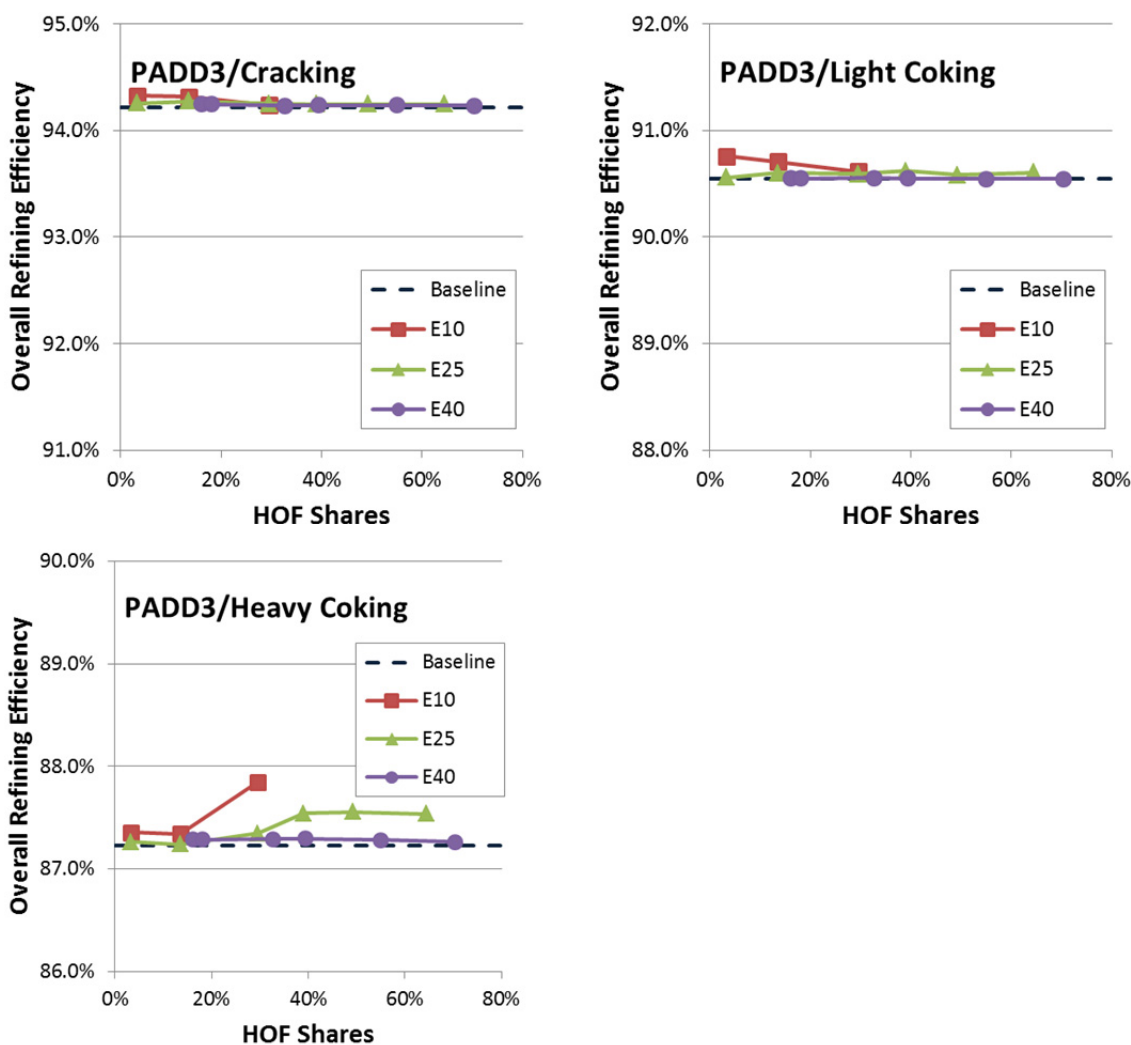


Figure 15 Overall refining efficiency versus HOF shares for each refinery configuration in PADD 3

increased fuel gas and hydrogen production offsets part of the NG purchase requirement, resulting in an overall refinery efficiency gain. However, such refinery efficiency gain is at the expense of the volumetric yield of liquid products, as mentioned earlier, which negatively affects the economics of the refinery.

Figure 16 provides the annual average overall refining efficiency versus HOF shares for each season (summer and winter) in PADD 3, averaging the three refinery configurations (cracking, light coking, and heavy coking). Similar to other overall refining efficiencies shown in Figure 15, the overall refining efficiencies for each season do not vary significantly by ethanol blending level and HOF share. Also, seasonal changes do not affect the overall refining efficiencies greatly.

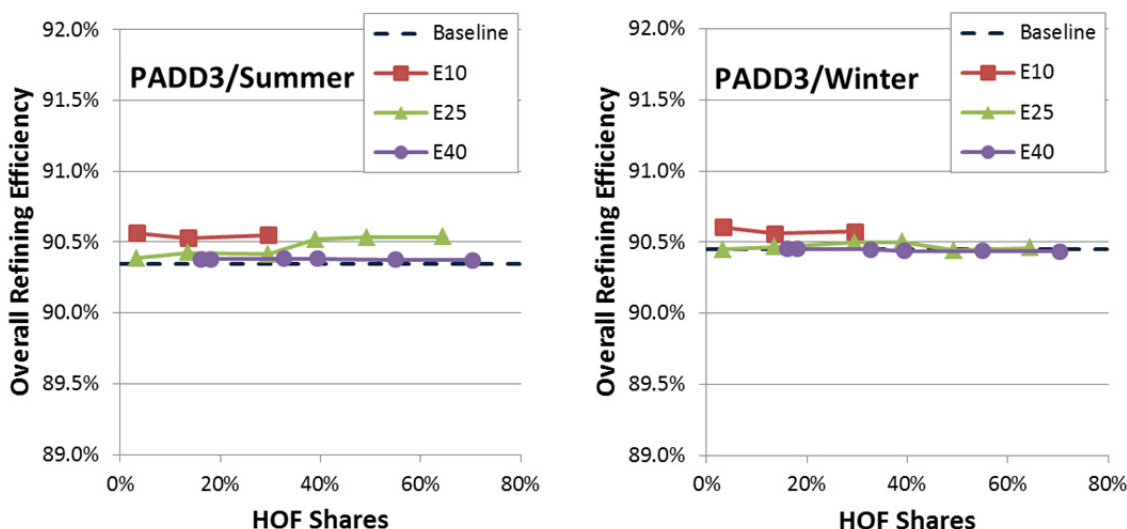


Figure 16 Overall refining efficiency versus HOF shares for summer and winter in PADD 3

5.3. Gasoline Refining Efficiency

The overall refining efficiency calculation considers an entire refinery as a single system, taking into account the refinery inputs and outputs. Even though the overall refining efficiency is critical for estimating the total processing energy use per unit of energy in all refinery products, the total processing energy use does not consider the differences in the energy intensities of the various refining units that produce the streams that make up the different product pools. Thus, the overall energy efficiency needs to be adjusted by using an energy consumption ratio for each product based on the energy intensity of the process units and their contribution to the various product pools.

5.3.1. Process-Level Efficiency

Figure 17 shows a schematic of a generic refinery process unit with various feeds or energy inputs (F_1 through F_k) and various yield streams or energy outputs (Y_1 through Y_j). Refinery energy inputs (e.g., crude, NG, hydrogen, electricity, and other hydrocarbons) are denoted by $Input_i$ in Figure 17. Refinery energy inputs and their derivatives propagate through successive process units to produce intermediate products and, eventually, final products. Thus, each stream's energy (feed F_k or yield Y_j) through a process unit carries certain energy burdens associated with the refinery inputs ($Input_1$ through $Input_i$). For example, EI_{ij} in Figure 17 denotes the energy burden of a specific refinery input i that contributes to the production of the unit energy of yield stream j . The sum of all energy burdens for a particular yield stream j is defined as the total energy intensity of that stream ΣEI_{ij} (i.e., the share of the total amount of refinery input energies required to produce the unit energy of that stream). Note that the inverse of energy intensity represents the energy efficiency. By estimating the production energy intensity of all streams and aggregating them for the products that make various final product pools (e.g., gasoline pool, distillate pool), we can obtain final product-specific efficiencies.

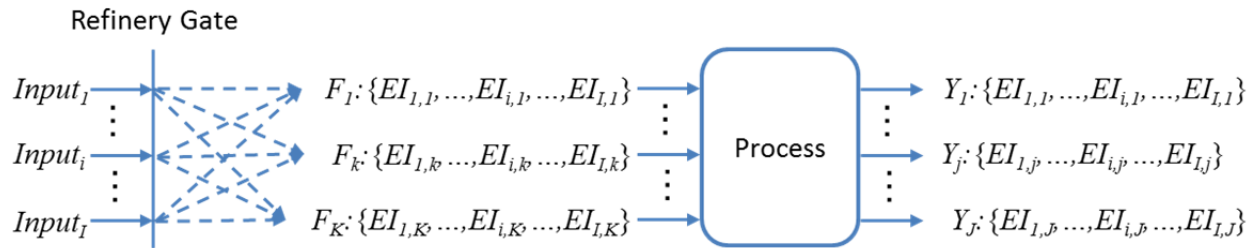


Figure 17 Schematic flow of a generic refinery process unit

For a given process, the energy burden (EI_{ij} in Btu/Btu) of a refinery input i to produce the unit energy of a given product yield (stream) j can be expressed by using the following equation:

$$EI_{i,j} = \left(\sum_k F_k \times EI_{i,k} \right) \times S_j \div Y_j$$

where F_k and Y_j are the energy in feed k and yield stream j to and from the process unit (in Btu/day), respectively, while S_j is the percentage contribution of yield j in all yield streams (Y_1 through Y_j) from a given process unit. The energy and emissions burden that is allocated to a yield stream j is defined by S_j . Note that waste streams such as sulfur are neglected and thus do not receive any energy and emissions burden from the process unit. Common metrics for allocating the energy burden to a yield stream by its share (S_j) in the total yield streams are

energy, market value, and mass allocations (Wang et al., 2004). In an energy-based allocation, the energy content of each stream is used to calculate its share (S_j^E). This is the most commonly used allocation metric in the life cycle of energy products because the significance of energy products is in their energy value. Because market values differ per megajoule of various fuels, a market-value-based allocation (S_j^M) would result in shares that are different from those calculated on the basis of energy allocation. Some analysts prefer market value allocation because refinery operation is typically optimized for maximum profit rather than maximum energy efficiency. However, the drawback of market value allocation is that there are periodic changes in the market values of most products based on varying market conditions. Argonne's previous analysis of 43 large U.S. refineries showed that the differences between energy-based and market-value-based allocations in determining product-specific efficiencies are not substantial except for coke (Elgowainy et al., 2014). In this analysis, mass-based allocation is not applicable because electricity generated from a general utility process cannot be characterized by mass. The energy-based shares of a yield stream j (S_j^E) can be expressed by the following equation:

$$S_j^E = Y_j \div \sum_j Y_j$$

In energy-based allocation, $El_{i,j}$ can be simplified further as follows:

$$El_{i,j} = \left(\sum_k F_k \times El_{i,k} \right) \times \left(Y_j \div \sum_j Y_j \right) \div Y_j = \left(\sum_k F_k \times El_{i,k} \right) \div \sum_j Y_j$$

Once the process-level allocation is applied to each of the process units in a refinery, the various process units are connected through their input/output relationships. Often, more than two yield streams are pooled into one stream (e.g., fuel gas or hydrogen) and used as feeds to subsequent processes. Even in cases in which the same materials are pooled together, their upstream energy burdens are separately tracked because their production pathways are different. After all processes are connected, the energy burdens of all streams in a refinery, including those for the final products, can be obtained. This procedure requires an iterative process because many feedbacks have to converge to a stable value. The iterative process results in product-specific energy intensities for each product (i.e., intensities are the contributions of each refinery input to produce a megajoule of each product). The inverse of the sum of the product-specific energy intensity is simply the product-specific refining efficiency.

5.3.2. Total (Domestic + Export) Gasoline Efficiency by PADD Region

Figure 18 shows the refining efficiency of the total gasoline pool versus HOF shares for PADDs 2 and 3. The total gasoline pool consists of domestic regular and HOF gasoline as well as export gasoline. The refining efficiency of the total gasoline pool in PADDs 2 and 3 are 2% and 2.6% lower, respectively, than the overall refining efficiency in each region shown in Figure 14. However, the ethanol blend levels and HOF shares have only a small impact of the total gasoline pool's refining efficiency (especially for E25 and E40 cases). The relatively unchanged gasoline efficiency with increasing HOF market share is a direct result of shifting the excess BOB from the domestic pool to the export pool. The difference in specifications between regular gasoline BOB and export gasoline BOB is small and thus did not affect the total (domestic + export) gasoline pool.

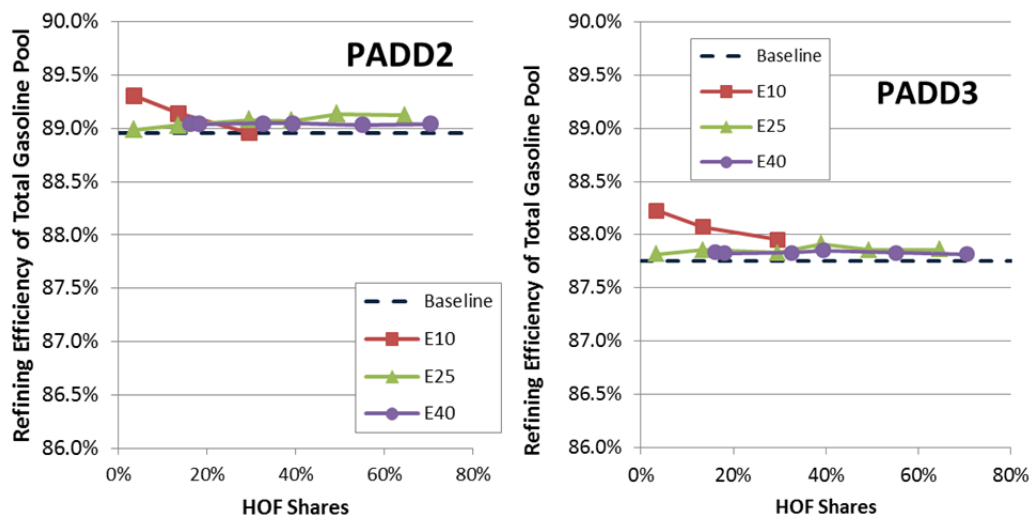


Figure 18 Refining efficiency of total gasoline pool versus HOF shares for PADDs 2 and 3

5.3.3. Total Gasoline Efficiency by Refinery Configuration

Figure 19 presents the refining efficiency of the total gasoline pool versus HOF shares for each refinery configuration in PADD 3. The impacts of ethanol blending levels and HOF shares on the refining efficiencies of the total gasoline pool are small even though they are more noticeable than the impacts on the overall refining efficiencies. Similar to the overall refining efficiencies, the variations in the refining efficiencies of the total gasoline pool are more prominent with lower ethanol blending levels (e.g., the E10 case) and greater refinery complexity (e.g., heavy coking).

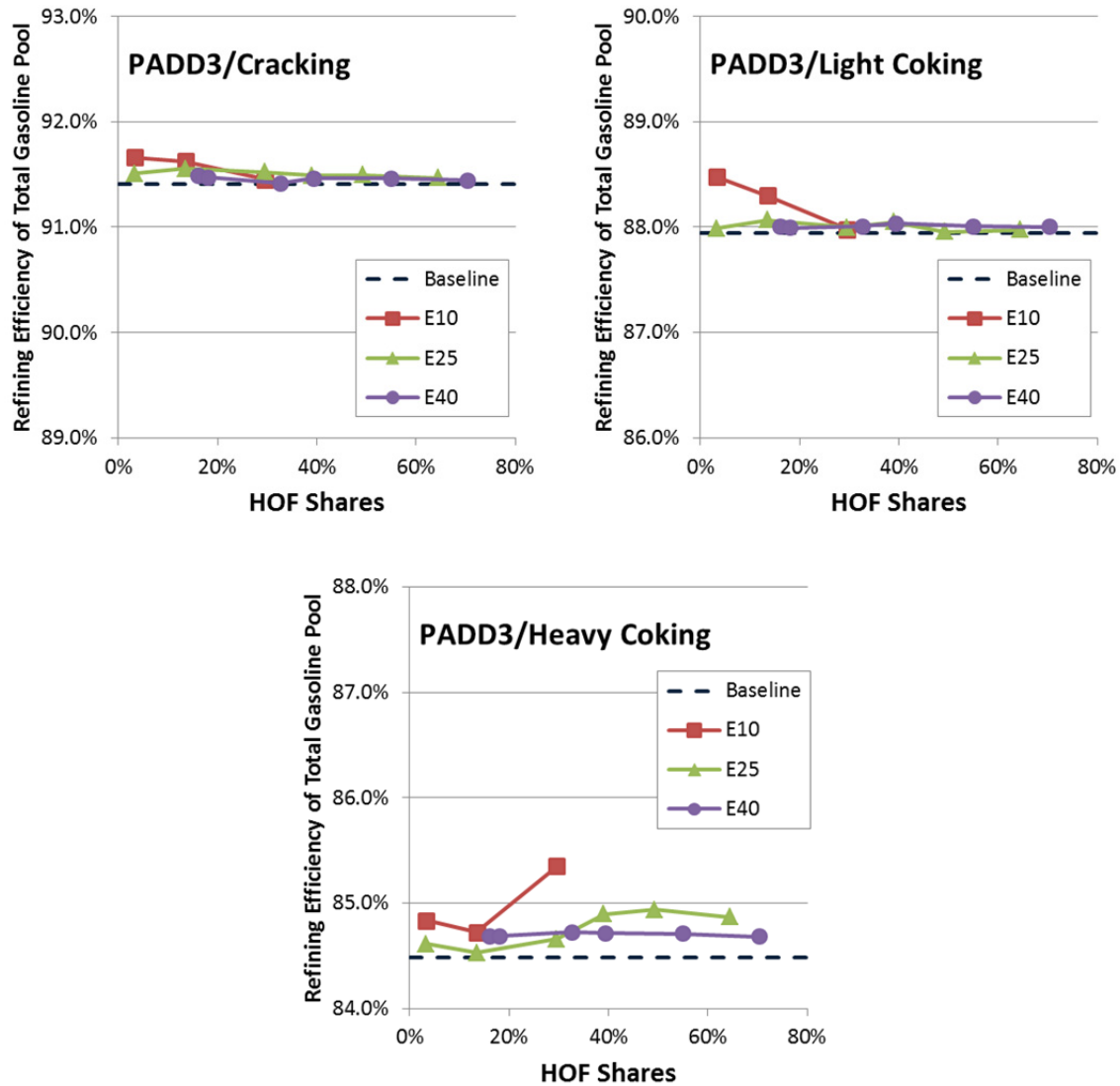


Figure 19 Refining efficiency of total gasoline pool versus HOF shares for each refinery configuration in PADD 3

5.3.4. Total Gasoline Efficiency by Season (Summer Versus Winter)

Figure 20 provides the refining efficiency of the total gasoline pool versus HOF shares for each season (summer and winter) in PADD 3. The summer gasoline refining efficiencies are 0.3% to 0.5% lower than the winter gasoline refining efficiencies because of the RVP requirements for the summer gasoline (see Table 2). The variations of the gasoline refining efficiencies for each season by ethanol blending levels and HOF shares are negligible.

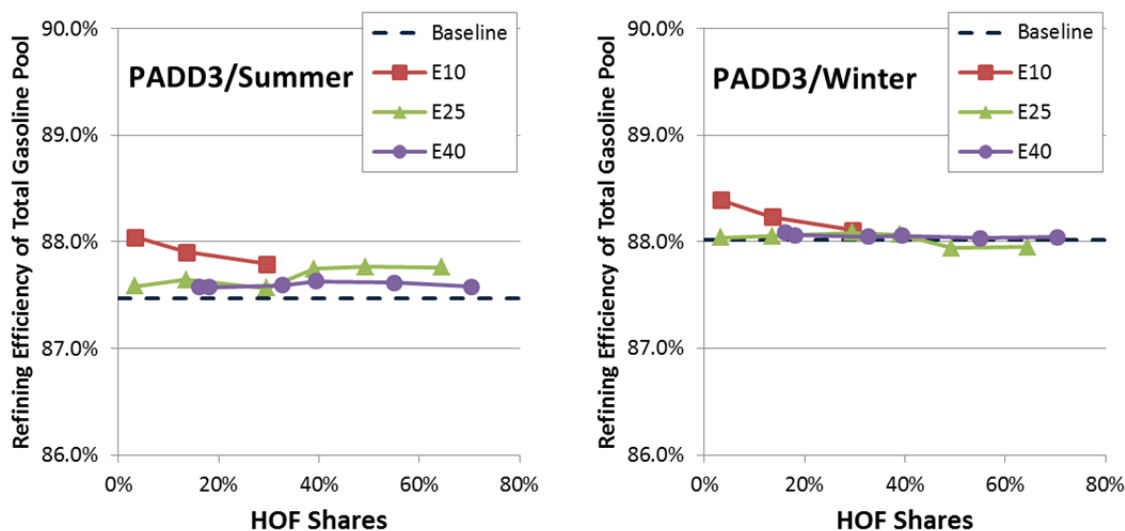


Figure 20 Refining efficiency of total gasoline pool versus HOF shares for summer and winter in PADD 3

5.3.5. Domestic Versus Export Gasoline BOB Efficiency

In general, the impacts of ethanol blending levels and HOF shares on the overall refining efficiencies and the total gasoline pool refining efficiencies are minimal. However, when the gasoline pool is separated into domestic BOB and export gasoline pools, their impacts become significant, especially for the export gasoline pool, as shown in Figure 21. Here, the domestic BOB pool includes the BOB pools for both regular and premium (e.g., HOF) gasoline. A key driver for the variations is the shares of gasoline components in the pools. Figure 22 presents the volumetric shares of gasoline components in domestic BOB and export gasoline pools for the E25 case in PADD 3 as an example. The domestic BOB pool is dominated by reformates and FCC gasoline, while the export gasoline pool is dominated by alkylate and isomerate. The domestic BOB employs more of the reformate (3–5 psi RVP) and FCC gasoline (7–9 psi RVP) to mitigate the impact of high-ethanol RVP in E25 (11.1 psi, see Table 1). The export pool is ethanol free and thus can accept components with a slightly higher RVP, such as alkylate (4–6 psi) and isomerate (13–15 psi). Furthermore, the export pool is restricted to 35% aromatics, thus limiting the acceptance of reformate in that pool. Such a limitation is absent in the U.S. markets (except for California); therefore, more reformate appears in the domestic BOB. The drop in refining efficiencies with HOF share in export gasoline is attributed to the increased production of alkylate as the HOF share increases. This inverse relationship between the gasoline refining efficiencies and alkylate production is a result of the high energy intensity of the alkylation process (Elgowainy et al., 2014). The reduction in export gasoline efficiency may arguably be attributed to increased HOF production. This issue is addressed in detail in the WTW section of this report. It is important to note that no significant efficiency changes were observed in other refinery products, except for LPG as shown in Appendix B. This is a designed

outcome since this study focused the response of the gasoline pool to holding the crude inputs and the demand for other products constant.

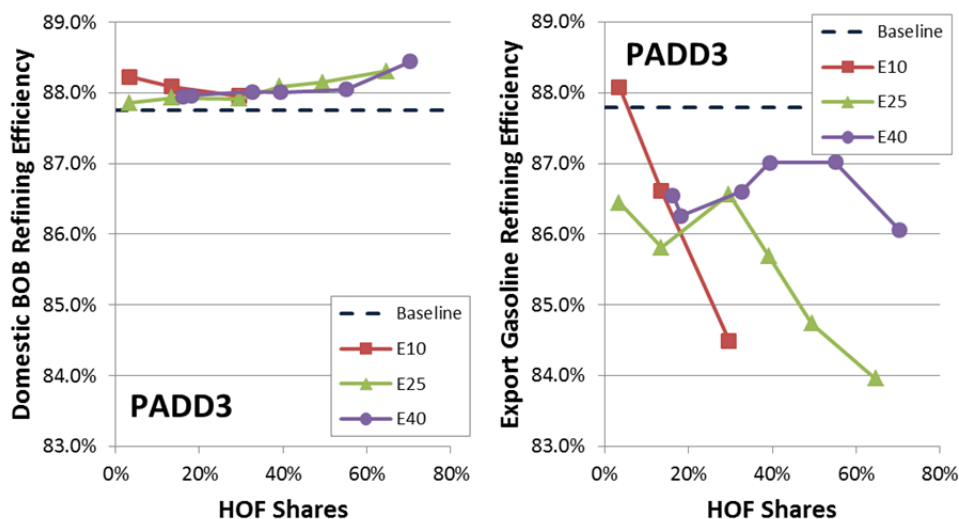


Figure 21 Refining efficiency of domestic BOB and export gasoline versus HOF shares in PADD 3

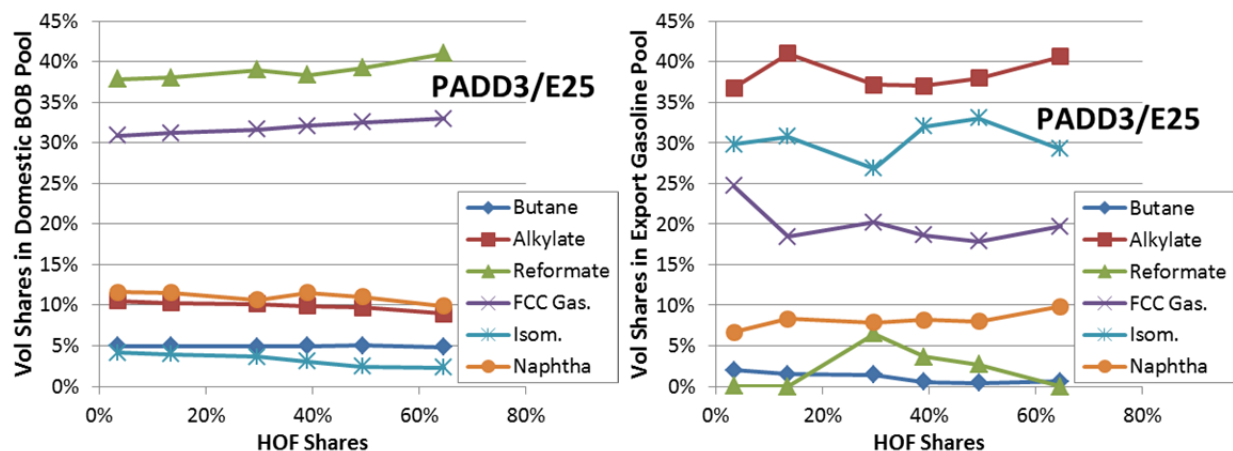


Figure 22 Volumetric shares of gasoline components in domestic BOB and export gasoline pools for the E25 Case in PADD 3

5.3.6. HOF Versus Regular Gasoline BOB Efficiency

When the domestic BOB pool is separated into HOF and regular gasoline BOB pools, the variations in the refining efficiencies of the BOB pools by ethanol blending levels and HOF shares are considerable, especially for the HOF BOB, as shown in Figure 23. The cause of the variations also can be found in the shares of gasoline components in the BOB pools. For example, Figure 24 shows the volumetric shares of gasoline components in the HOF and regular BOB pools for the E25 case in PADD 3. Both pools are generally dominated by reformates. Also,

in the HOF BOB pool, reformates replace alkylates almost directly as HOF shares increase from 3% to 39%. Because a reformer is more efficient than an alkylation unit and because it co-produces hydrogen, the energy intensity of reformates is much lower than that of alkylates. Thus, the displacement of alkylates by reformates contributes to the increases in the HOF BOB refining efficiencies in the E25 case.

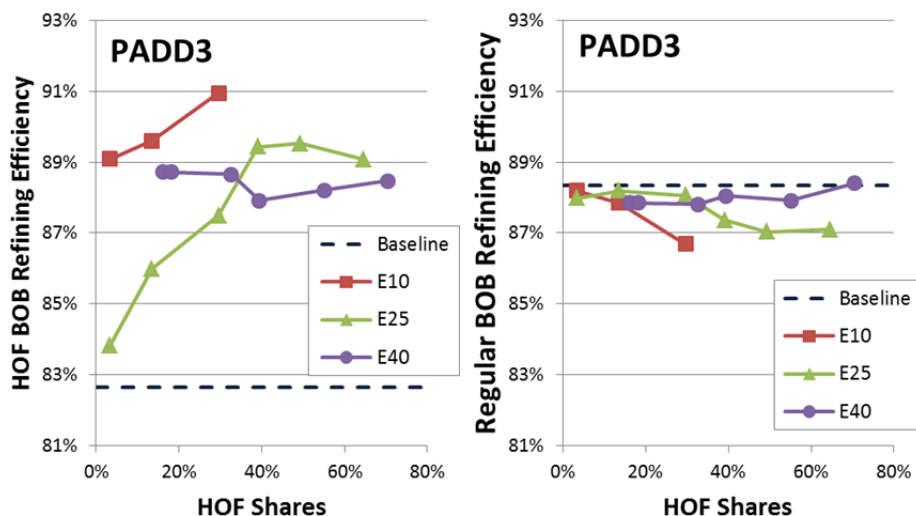


Figure 23 Refining efficiency of HOF and regular BOB Versus HOF shares in PADD 3

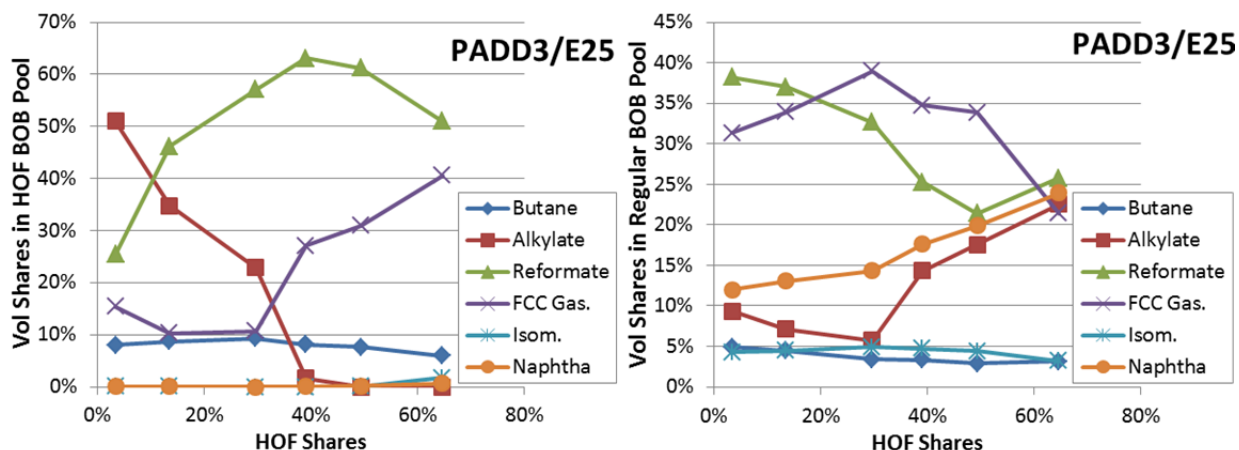


Figure 24 Volumetric shares of gasoline components in HOF and regular BOB pools for the E25 case in PADD 3

5.4. Summary of LP Modeling Results and Refining Efficiency Calculation

The refining efficiency of the total gasoline pool is largely unaffected by ethanol blending levels between 20% and 40% and HOF shares. However, when the pool is segregated into regular and HOF BOB pools and an export gasoline pool, the refining efficiency of each pool varies considerably depending on the ethanol blending levels and HOF shares. A driver for the variations in the refining efficiencies of the segregated pools is the share of gasoline components in each respective pool. Note, however, that the pools may not have a unique composition; some uncertainties in the compositions of BOB and gasoline pools may exist, and they will be different for specific refinery operations. This is because multiple blending recipes can exist that can satisfy the desired gasoline specifications without having a significant effect on the refinery margin. The LP model might be able to find solutions by using different BOB and gasoline pools that result in equivalent profit and fuel specifications within a numerical tolerance. Thus, the refining efficiencies and volumetric shares of the segregated pools need to be evaluated with that possible variation in mind. The impacts that would result from shifting BOB from the domestic gasoline pool to the export pool are examined in detail in Section 8.

6. Vehicle Efficiency Gains

The high RON of HOF provides improved anti-knock behavior. The minimum spark advance for the best torque region of the engine map can be extended to higher brake mean effective pressure (BMEP) values with improved anti-knock behavior (Kalghatgi, 2001; Mittal and Heywood, 2009; Stein et al., 2012). If an engine is designed to take advantage of the improved anti-knock behavior of HOF (e.g., with a higher compression ratio), the engine efficiency can be increased significantly, which can be translated to vehicle fuel economy through downsizing and downsizing. With vehicle simulations of FTP-75 and HWFET drive cycles, Speth et al. (2014) estimated that, with 98 RON gasoline, increasing the compression ratio of an engine can reduce its fuel consumption by 2.2% – 3.2% without downsizing, and by 3.0% – 4.5% with downsizing, below the consumption of a baseline naturally aspirated engine. Muñoz et al. (2005) estimated an improvement of about 3% in an engine's efficiency as its compression ratio increases by one point. Nakata et al. (2007) found that, at partial load, the thermal efficiency of a lean boosted engine can be improved from 35% to 39% by increasing the compression ratio from 10 to 13 with 92 RON gasoline, and it can be further improved to 41.9% (i.e., by 7.4%) at a compression ratio of 13 when RON is raised from 92 to 100. However, it is important to note that the improvement might not be realized for highly loaded cycles, such as U.S. driving cycles. Recently, Leone et al. (2014) found that, depending on drive cycles, the increase in vehicle efficiency for 101 RON gasoline and a compression ratio of 13 could range from 5.5% to 8.8% relative to 91 RON gasoline and a compression ratio of 10. Similarly, Hirshfeld et al. (2014) found that increasing an engine's 10:1 compression ratio to 12:1 and to 13:1 can increase the vehicle's efficiency by 5% – 7% and by 6% – 9%, respectively. The relative increase in a vehicle's efficiency per the increase in its engine efficiency is in a range of 0.94 to 1.23 (Speth et al., 2014).

As mentioned before, blending more ethanol for HOF production decreases its volumetric energy density. Thus use of E25 results in about 5% energy loss per HOF gallon compared to E10, which can be compensated for by the aforementioned 6% – 9% increase in vehicle efficiency. Based on the above studies, ORNL recommended the use of 5% MPGGE fuel economy gain as the base case in this study for 100 RON HOF. The volumetric energy density loss for E40 is about 10% when compared to E10. However, if RON is fixed, in direct injection engines, the heat of vaporization effect from increased ethanol content (e.g., E40) can improve the high load efficiency by reducing the use of spark retarding (Leone et al., 2014). Thus, the 10% volumetric energy loss in E40 compared to E10 could potentially be compensated for when one considers the high end of the vehicle efficiency gain from previous studies (9%) and the additional efficiency benefits from the heat of vaporization effects of ethanol in E40. This forms the basis for the sensitivity case of 10% MPGGE fuel economy gain assumed in this study for

HOF E40. Table 10 shows a summary of the various studies and the vehicle efficiency gains used in this study.

Table 10 Summary of the engine and vehicle efficiency gain from various studies

Reference	RON	Efficiency Gain (%)		Comment
		Engine	Vehicle	
Nakata et al. (2007)	100	7.4		Constant load, compression ratio = 13
Leone et al. (2014)	102		5.5–8.8	Compression ratio = 13
Speth et al. (2014)	98		2.2–3.2 without downsizing, 3.0–4.5 with it	
This study	100		5	10% for E40 as a sensitivity case

7. Well-to-Wheels Stages and System Boundary

The system boundary for the WTW analysis of HOF consists of petroleum gasoline, corn ethanol, and corn stover ethanol pathways, as illustrated in Figure 25. Corn stover ethanol is used as an example of cellulosic ethanol in this study. Each pathway includes feedstock recovery (crude recovery, corn farming, or corn stover collection), feedstock transport, fuel production (petroleum refining or ethanol production), fuel transportation and distribution (T&D), and HOF combustion in vehicles.

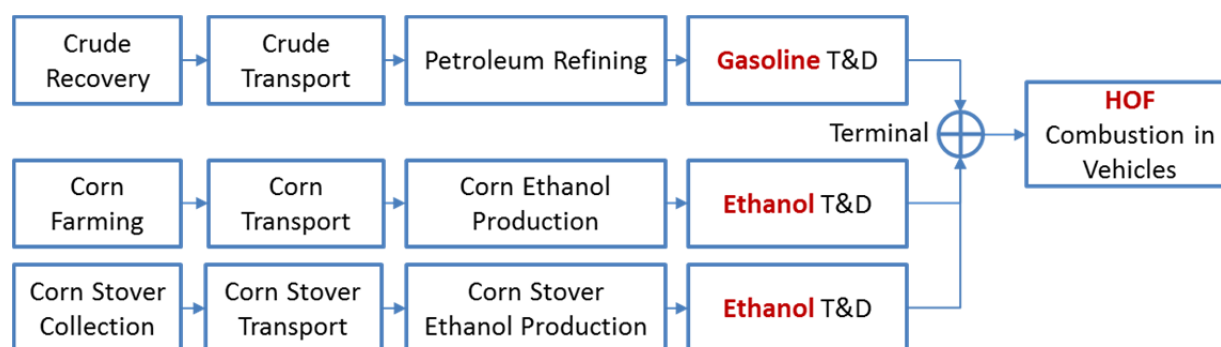


Figure 25 System boundary for the WTW analysis of HOF

7.1. Crude Recovery

The WTW analysis of gasoline BOB and other hydrocarbon blending components covers the upstream stages of crude recovery. The U.S. refining industry processes crude oils with different qualities from various sources, including Canada, Mexico, the Middle East, Latin America, Africa, and other regions, as well as domestic production. Table 11 presents the shares of crude oils to U.S. refineries in 2013 and 2020 and to refineries in PADDs 2 and 3 in

Table 11 Shares (%) of crude oils to U.S. refineries in 2013 and 2020 and to PADDs 2 and 3 refineries in 2020

Refinery Shipment	U.S. Domestic	Canada Oil Sands	Canada Conv. Crude	Mexico	Middle East	Latin America	Africa	Others
U.S. 2013 ^a	49.1	9.4	7.6	5.6	13.2	9.9	4.2	1.0
U.S. 2020 ^a	46.7	13.9	8.5	6.5	5.7	8.4	8.1	2.2
PADD 2 2020 ^b	56.8	34.7	8.4	—	—	—	—	—
PADD 3 2020 ^b	51.9	4.2	21.9	21.9	—	—	—	—

^a Based on U.S. EIA (2014b, 2014c) and CAPP (2012).

^b Estimated from the projections by U.S. EIA (2014b, 2014c) with inputs from the DOE Office of Energy Policy and Systems Analysis.

2020. The shares to U.S. refineries are based on U.S. EIA (2014b, 2014c) and CAPP (2012), while the shares to refineries in PADDs 2 and 3 refineries are estimated in this study based on U.S. EIA (2014b, 2014c) with inputs from the DOE Office of Energy Policy and Systems Analysis. In general, the crude supplied to U.S. refineries can be categorized into conventional crude and oil sands. U.S. EIA (2014b, 2014c) and CAPP (2012) project the oil sands share in the crude mix to U.S. refineries to grow from 9% today to 14% in 2020. The oil sands share is even higher in PADD 2, at 35%, due to the available transportation logistics of oil sands to PADD 2.

In this study, Argonne examined the oil sands pathways in detail by using the energy intensity provided by Englander et al. (2015) or different oil sands recovery operations (i.e., surface mining and in situ) and various crude products from these operations (i.e., upgraded SCO and diluted bitumen [dilbit]). Almost half of the oil sands products in 2012 were from surface mining, while in situ production accounted for the remainder. Furthermore, approximately 44% of the bitumen produced from surface mining is upgraded to SCO, while only 6% of the bitumen produced from in situ operations is upgraded to SCO. The bitumen (from mining and in situ operations) is mixed with diluents, such as natural gas condensate or naphtha, that reduce the density and viscosity of the blend (dilbit) and thus facilitate its shipment to refineries (Englander et al., 2015). The system boundary and operational activities for oil sands products are shown in Figure 26. Table 12 summarizes the GHG emissions from conventional crude recovery and the different oil sands recovery and upgrading operations, including GHG emissions from land disturbance associated with bitumen recovery, as provided in Yeh et al. (2014).

The oil sands share in the crude mix is a key WTW analysis parameter because of the difference in GHG intensities of conventional crude recovery and oil sands recovery, as shown in Figure 27. The GHG intensities of conventional crude recovery are lower than those of oil sands recovery. A similar effort conducted by Carnegie Endowment for International Peace develops an oil climate index (OCI), which estimates the life-cycle GHG emissions of individual oils (in kg CO₂-e per crude barrel equivalent (Carnegie Endowment for International Peace, 2015)

The GHG intensities of conventional crude oil recovery in this study are based on GREET's default assumptions for conventional crude recovery (Burnham et al., 2011). The key parameters affecting GHG intensities in the conventional crude recovery stage are as follows:

- Crude oil efficiency (98.0% in GREET),
- CO₂ emissions from associated gas flaring (1.4 g/MJ in GREET), and
- CH₄ emissions from associated gas venting (0.084 g/MJ in GREET).

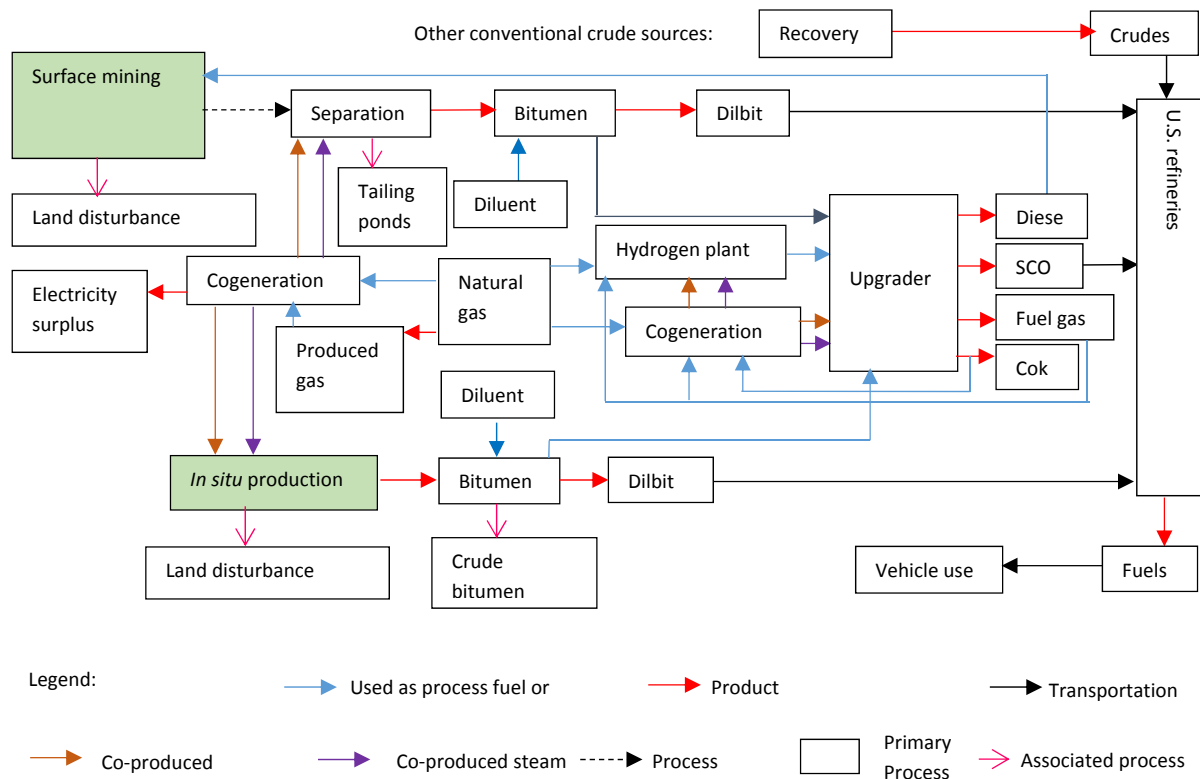


Figure 26 System boundary and process stages of oil sands production

Table 12 GHG emissions (g CO₂-e/MJ of gasoline) from various oil sands recovery and production operations (Cai et al., 2015)

Process	Conv. Crude	Mining + SCO	Mining + Bitumen	In Situ + SCO	In Situ + Bitumen
Recovery	4.4	20.1	7.8	26.0	16.8
Transportation	1.5	2.7	3.9	2.7	3.9
Refining	12.5	12.1	14.0	12.2	14.0
Fuel combustion	73.2	73.2	73.2	73.2	73.2
WTW	92.3	108.8	99.5	114.7	108.5

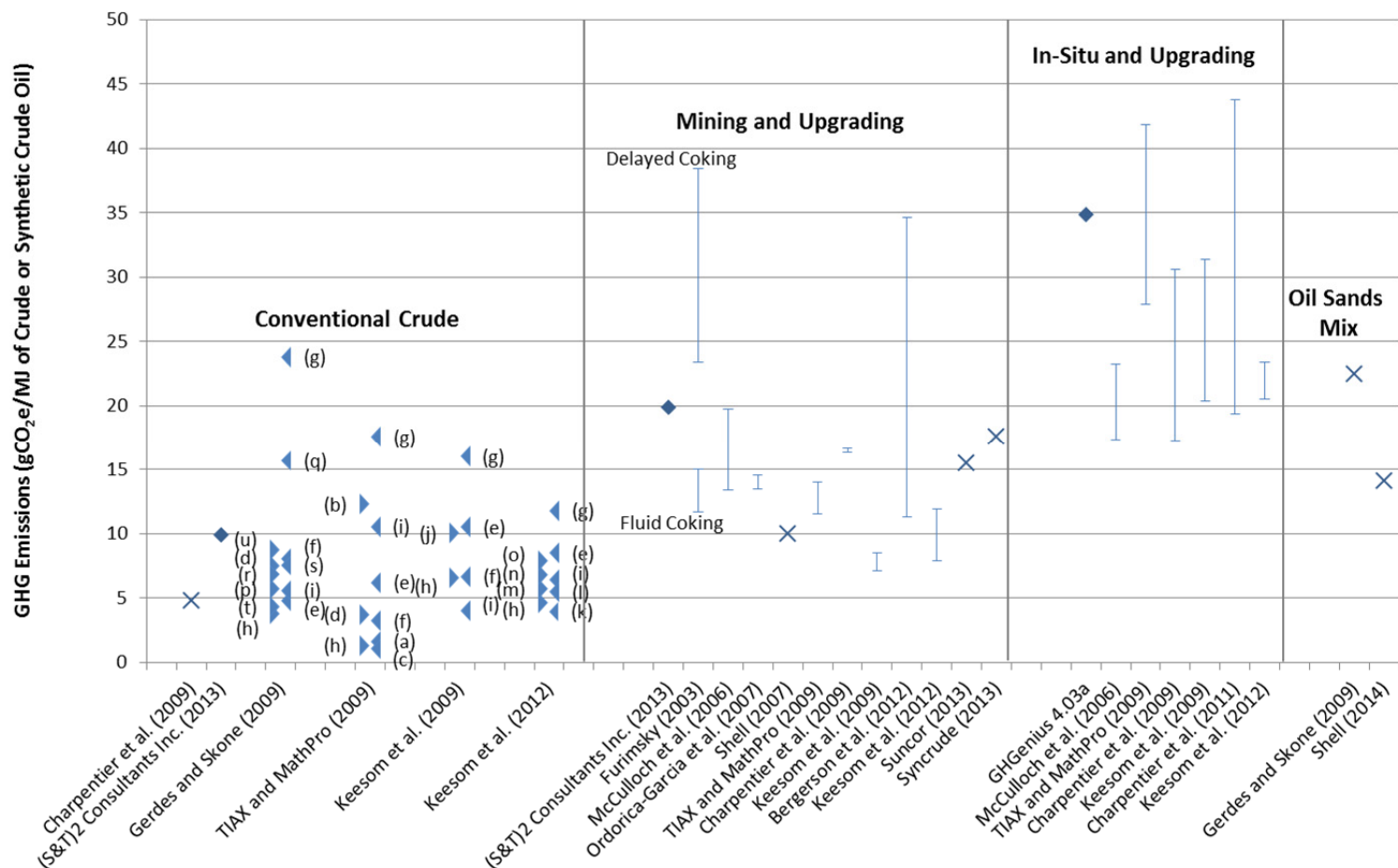


Figure 27 GHG intensity of conventional crude and synthetic crude oil from various sources (Keesom et al., 2012; Charpentier et al., 2009; (S&T)2 Consultants Inc., 2013; Gerdes and Skone, 2009; TIAX and MathPro, 2009; Keesom et al., 2009; Furimsky, 2003; McCulloch et al., 2006; Ordorica-Garcia et al., 2007; Shell, 2007; Bergerson et al., 2012; Suncor, 2013; Syncrude, 2013; Shell, 2014) For Gerdes and Skone (2009), TIAX and MathPro (2009), and Keesom et al. 2009 and 2012: (a) Alaska North Slope, (b) California Heavy, (c) West Texas Intermediate, (d) Canada Heavy, (e) Iraq, (f) Mexico, (g) Nigeria, (h) Saudi, (i) Venezuela, (j) MARS, (k) North Sea, (l) Brazil, (m) Libya, (n) Iran, (o) Russia, (p) United States, (q) Angola, (r) Ecuador, (s) Algeria, (t) Kuwait, and (u) Other.)

7.2. Petroleum Refining

The major refinery inputs include crude, NG, butane, and electricity. Figure 28 shows the aggregate average energy intensity of all examined refinery configurations and HOF market scenarios for gasoline BOBs (E10 HOF, E25 HOF, and E40 HOF) in PADDs 2 and 3. Also, the baseline represents the current market share of premium E10 (93 AKI) and regular E10 gasoline (87 AKI), which account for 8% and 92% market shares, respectively. The average of the energy intensities of gasoline BOB for all HOF market scenarios and refinery configurations is within a narrow range of 1.11 MJ/MJ to 1.14 MJ/MJ for the HOF cases (E10, E25, and E40). However, the variations between different refinery configuration and HOF market scenarios (shown by error bars) are significant for some HOF cases. The error bars denote the minimum and maximum of total energy intensities in each HOF case, considering all HOF market shares and averaging all three refinery types by the shares shown in Table 4 and the two seasons (summer and winter). Note that the sum of energy intensities is the inverse of the product-specific efficiency. As noted in Section 5.3.5, there is a reduction in the export gasoline efficiency (i.e., increase in its energy intensity), especially for high ethanol blending levels (e.g., E40), that may be attributed to increased HOF production (see Figure 21). We allocate the additional energy intensity in the gasoline export pool to the corresponding BOB pool for each of the HOF cases, as shown in Figure 28.

It is important to note that gasoline BOB in PADD 3 for the E10 HOF case has a lower energy intensity than the intensities for the E25 and E40 HOF cases. The decrease in the energy intensity of HOF E10 is an artifact of the no-RFG assumption in the HOF E10 cases, which relaxes the RVP constraint significantly. As mentioned above, the no-RFG assumption was applied because RFG's summer RVP constraint cannot be met without additional capital investment.

Figure 29 shows the energy intensities of gasoline BOBs for the various HOF cases by refinery configuration in PADD 3. As the refinery becomes more complex, from cracking to light coking and to heavy coking, the energy intensity increases, especially as a result of the large requirement for NG in the coking configurations.

Figure 30 shows the energy intensities of gasoline BOBs for the various HOF cases by season in PADD 2. The largest difference between the summer and winter premium BOB is the amount of butane. Due to the higher RVP value in winter, refineries can blend more butane in the winter premium BOB, which increases the refineries' profit margin.

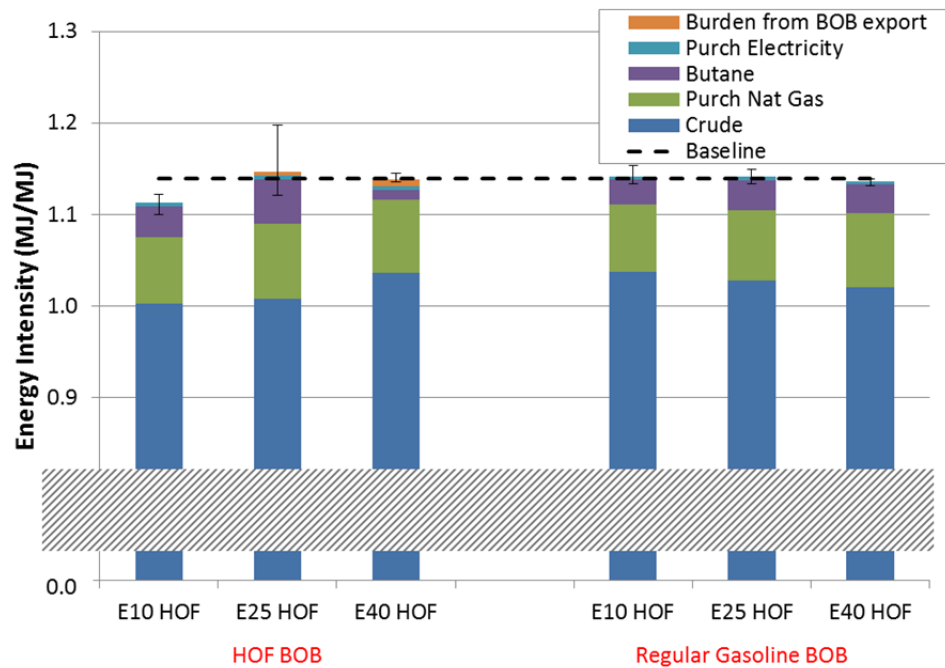


Figure 28 Energy intensities of gasoline BOBs for the E10 HOF, E25 HOF, and E40 HOF cases in PADD 3

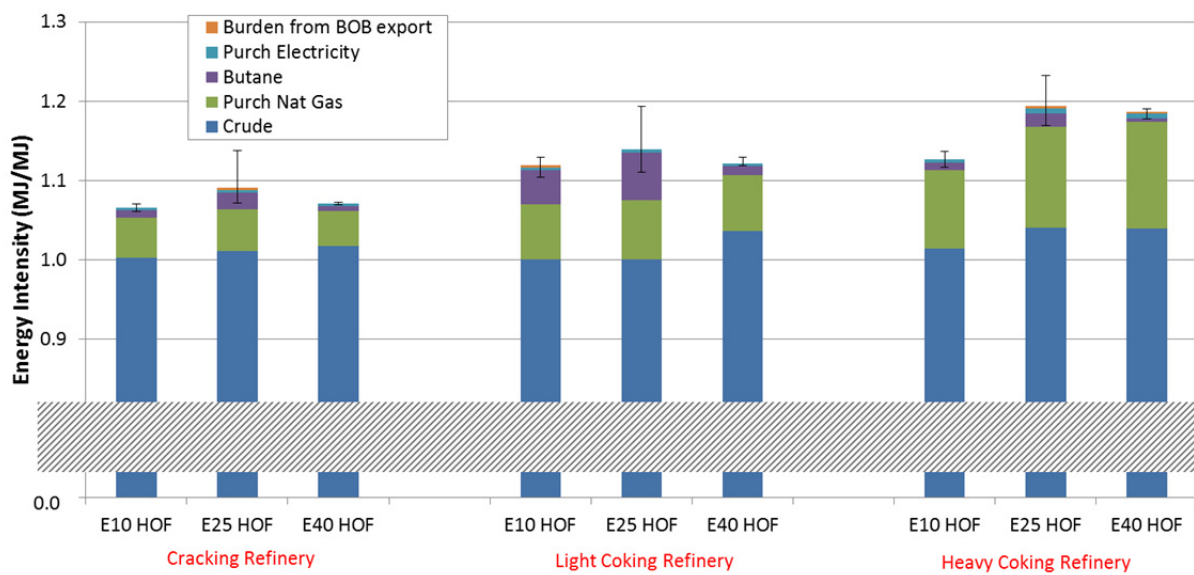


Figure 29 Energy intensities of gasoline BOBs for the E10 HOF, E25 HOF, and E40 HOF cases by refinery configuration in PADD 3

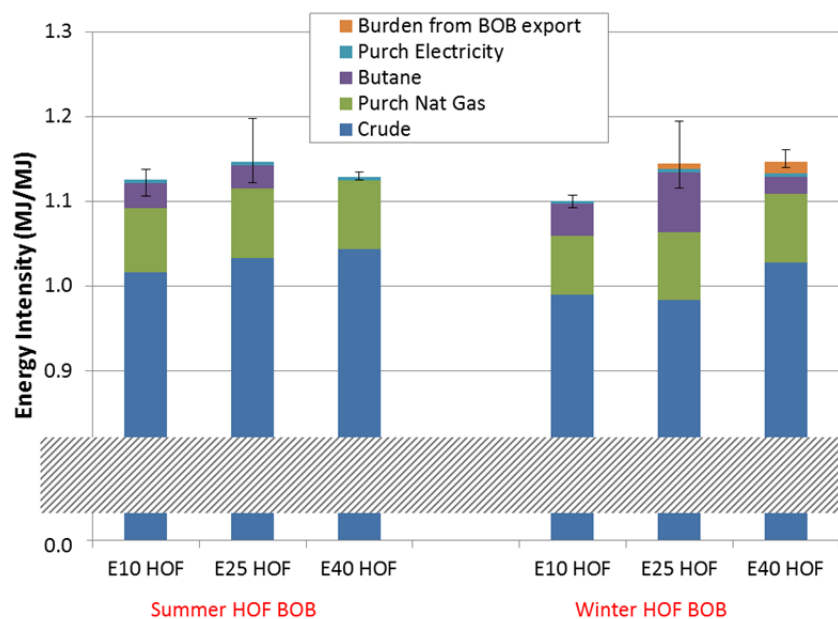


Figure 30 Energy intensities of gasoline BOBs for the E10 HOF, E25 HOF, and E40 HOF cases by season in PADD 3

7.3. Ethanol Production

The production of corn ethanol in the United States had increased to more than 14.3 billion gallons in 2014 since the beginning of the U.S. ethanol program in 1980 (Renewable Fuels Association, 2015). The increase after 2007, the year the Energy Independence and Security Act came into effect, was remarkable. Corn-ethanol is currently being used as a blending component to produce regular and premium gasoline (E10). Over the long term, the growth potential for bioethanol production lies in the use of cellulosic feedstocks, which include crop residues (e.g., corn stover, wheat straw, and rice straw), dedicated energy crops (e.g., switchgrass, miscanthus, mixed prairie grasses, and short-rotation trees), and forest residues. The resource potential of these cellulosic feedstocks can support a large amount of biofuel production. For example, in the United States, nearly 1 billion dry tons of these resources are potentially available each year (West et al., 2009). The 1 billion dry tons of biomass can be translated into 80 billion gallons of potential ethanol production per year with a conversion of 80 gal of ethanol per dry ton of biomass. This volume is significant, even when compared to the annual U.S. consumption of gasoline, at 200 billion ethanol-equivalent gallons (U.S. EIA, 2014d).

Producing 100 RON HOF in a refinery via blending with high RON refinery components (i.e., reformate and alkylate) or with ethanol affects its economics and depends mainly on the cost spread between these two options. However, the energy and GHG emissions intensities of these two options are significantly different and need to be evaluated on a WTW basis.

Argonne continuously expands and updates the GREET model to evaluate the life-cycle GHG emissions associated with transportation fuels and vehicle technologies on a consistent basis (Argonne National Laboratory, 2014). Among the more-than-100 fuel production pathways, the GREET model covers both petroleum gasoline and bioethanol production pathways. The system boundaries and activities covered by the LCA of corn ethanol are shown in Figure 31. Wang et al. (2012) documented GREET ethanol pathway key parameters and estimated WTW GHG emissions of ethanol from corn and from corn stover, including direct and indirect land use change impacts. Detailed modeling of land use changes of ethanol pathways is documented in Dunn et al. (2013).

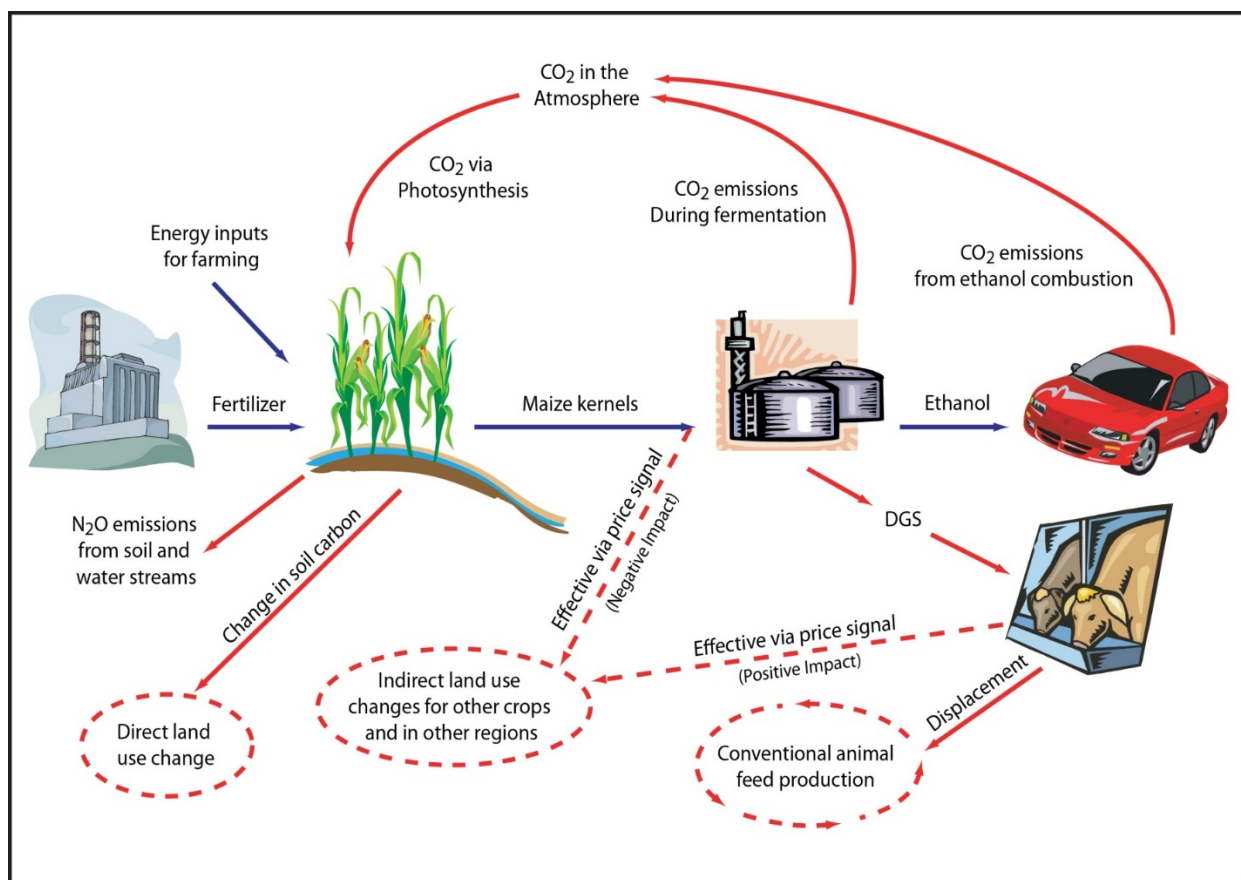


Figure 31 System boundaries for corn ethanol life cycle

Key WTW parameters for corn and corn stover ethanol pathways are summarized in Table 13. Several updates were made to reflect changes in the ethanol pathways since Argonne's ethanol study in 2012 (Wang et al., 2012). The fertilizer applications for corn farming were updated with the latest survey by the National Agricultural Statistics Service of the U.S. Department of Agriculture (USDA, 2014). Also, the corn ethanol production process was updated based on Mueller and Kwik (2013). A key change in the GREET's corn ethanol pathway is the implementation of a dry milling corn ethanol plant with corn oil extraction. Recently, the share

of ethanol plants with corn oil extraction has been increasing because corn oil recovery could increase the value of distillers' grain with solubles (DGS), reduce the NG consumption for drying DGS, and add a more valuable by-product (i.e., corn oil) (Riley, 2013). Note that the corn stover ethanol production assumptions were based on NREL's techno-economic analysis, which assumed commercial-scale plants.

Table 13 Key WTW parameters for corn and corn stover ethanol pathways

Parameter: Unit	Corn			Corn Stover
Corn farming/corn stover collection (per dry tonne of corn or corn stover, except as noted)				
Direct energy use: MJ	421 ^a			224 ^b
N fertilizer application: kg	17.6 ^b			7.72 ^b
P fertilizer application: kg	6.06 ^b			2.20 ^a
K fertilizer application: kg	6.29 ^b			13.2 ^a
Limestone application: kg	47.8 ^a			
N ₂ O conversion rate of N fertilizer: %	1.525 ^a			
Corn/corn stover ethanol production				
Parameter: Unit	Dry Mill without Corn Oil	Dry Mill with Corn Oil	Wet Mill	Con Stover
Ethanol yield: L/dry tonne of corn or corn stover	510 ^b	514 ^b	476 ^b	376 ^a
Ethanol plant energy use: MJ/L of ethanol	7.49 ^a	7.36 ^b	13.2 ^a	
DGS yield: kg (dry matter basis)/L of ethanol	0.675 ^a	0.646 ^b		
CGM yield: kg (dry matter basis)/L of ethanol			0.147 ^a	
CGF yield: kg (dry matter basis)/L of ethanol			0.632 ^a	
Corn oil yield: kg (dry matter basis)/L of ethanol		0.023 ^b	0.117 ^a	
Electricity yield: kWh/dry tonne of corn stover				226 ^a
Enzyme use: g/dry kg of corn or corn stover	1.04 ^a	1.04 ^b	1.04 ^a	15.5 ^a
Yeast use: g/dry kg of corn or corn stover	0.36 ^a	0.36 ^b	0.36 ^a	2.49 ^a
Corn ethanol shares: percent	18 ^b	73 ^b	9 ^b	

^a Based on Wang et al. (2012)

^b Based on Wang et al. (2014)

Historically, GREET considers corn stover as an agricultural residue, not a co-product, of corn farming because harvest practices and seed development are focused on grain yield increases and not on maximizing stover yield. Thus, only the energy that is consumed during the harvesting pass to collect the stover and to apply supplemental fertilizer to replenish the nutrients in the harvested stover is attributed to corn stover. As corn stover becomes a promising biofuel feedstock, it could be regarded as a co-product instead of as a residue or waste stream of corn production. The new GREET version now allows users to allocate corn-farming burdens between corn grain and corn stover by energy allocation, mass allocation, and market-value allocation, in addition to allowing the attributional approach. More details can be found in Wang et al. (2014). The WTW analysis of this study continues to treat corn stover as a waste residue.

7.4. Vehicle Operation

Since this study investigates on the relative benefit of HOF and HOFV, the relative vehicle efficiency gain by HOFVs, rather than the absolute fuel economies of HOFVs and regular E10 (or non-HOF) vehicles, would be critical. As discussed in Section 6, a 5% vehicle efficiency gain is assumed for HOF vehicles relative to regular E10 vehicles. This study also considers a sensitivity case of a 10% vehicle efficiency gain with E40 due to the additional benefits of the increased ethanol blending level mentioned above (e.g., reduced use of spark retard). Note that the vehicle efficiency of regular E10 vehicles would be improved in the future because of various technology advances (e.g., vehicle lightweighting, aerodynamic drag reduction, tire rolling resistance reduction, continuous valve timing, cylinder deactivation), and the 5% vehicle efficiency gain is applied on top of the regular E10 vehicles' efficiency gain.

In order to present per-mile results that account for the impact of vehicle efficiency gains, this study uses 23.9 miles per gallon (mpg) for the fuel economy of the regular E10 vehicles, which is the average of the fleet-average on-road fuel economies of non-HOFVs with E10 gasoline in all scenarios estimated by NREL's ADOPT model. Thus, 5% and 10% vehicle efficiency gains result in 25.1 and 26.3 MPGE (miles per gasoline gallon equivalent). We acknowledge that the ADOPT-estimated fuel economy of non-HOFVs is substantially lower than the fleet average on-road fuel economies estimated by EIA, which were 26.2 and 32.3 mpg in 2022 and 2030, respectively (U.S. EIA, 2014d). However, if the same vehicle efficiency gains is assumed for the EIA's projection, the relative energy and emissions benefits would be consistent with those presented in Section 8.4.

8. HOF WTW Results

8.1. Impacts of HOF Refining Energy Intensity

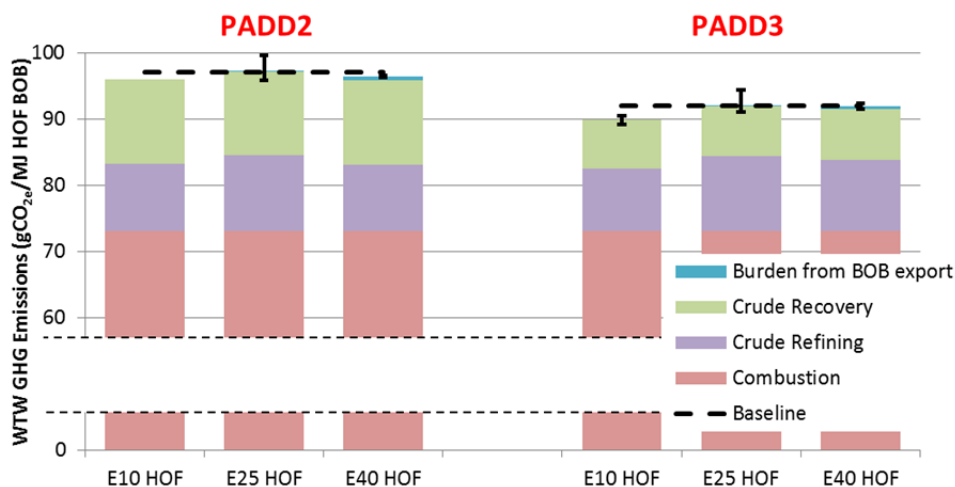
Figure 32 provides the WTW GHG emissions (g CO₂-e/MJ of HOF BOB) and petroleum use (MJ/MJ of HOF BOB) associated with BOB for E10, E25, and E40 HOF in PADDs 2 and 3 as an aggregate average of all examined refinery configurations and HOF market scenarios. The impacts of the variation among different refinery configuration and HOF market scenarios are denoted by error bars in each HOF case. In the figure, the baseline denotes the WTW petroleum use and GHG emissions associated with BOB for business-as-usual gasoline. The business-as-usual gasoline consists of 92% regular E10 and 8% premium E10 but without 100 RON HOF production. The averages of the WTW results for HOF BOB are not significantly different from the baseline BOB values. Note that the baseline and HOF BOB include no ethanol. The small impact of refinery changes on the WTW results can be explained by the small changes in HOF BOB energy intensities shown earlier in Figure 28. The WTW GHG emissions in PADD 2 are slightly larger than those in PADD 3 because of the higher GHG intensities associated with oil sands. As noted in Section 5.3.5, there is a reduction in the export gasoline's efficiency (i.e., an increase in its energy intensity), especially with regard to high ethanol blending levels (e.g., E40), that could be attributed to increased HOF production (see Figure 21). We allocated the additional GHG emissions in the gasoline export pool to the corresponding BOB pool for each of the HOF cases, as shown in Figure 32. The impact of that burden on HOF from the export pool is rather small (less than 1 g CO₂-e/MJ).

8.2. Additional Impacts of Ethanol Blending

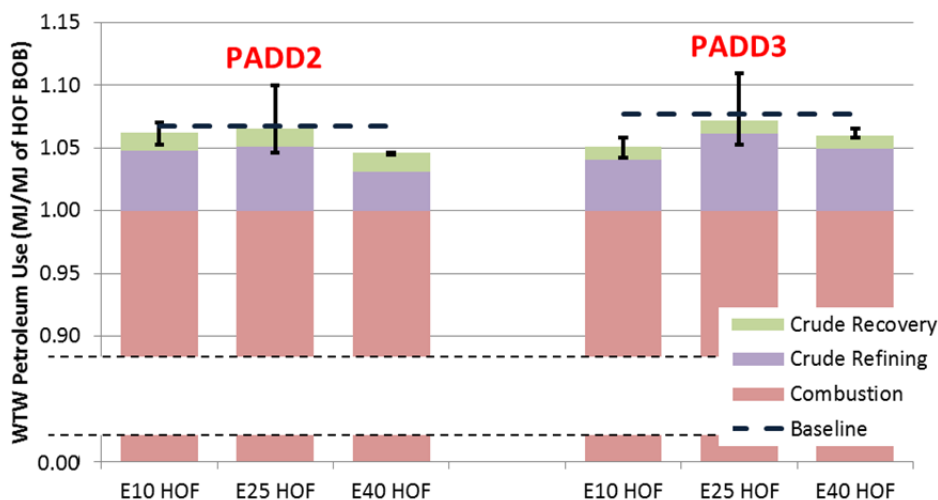
Figure 33 shows WTW emissions (g CO₂-e/MJ of HOF) associated with E10, E25, and E40 HOF blended with corn and corn stover ethanol in PADDs 2 and 3. Similarly, Figure 34 presents WTW petroleum use (in MJ/MJ of HOF) associated with E10, E25, and E40 HOF blended with corn and corn stover ethanol in PADDs 2 and 3. The baseline in the figures denotes the WTW petroleum use and GHG emissions associated with business-as-usual E10 gasoline, consisting of 92% regular E10 and 8% premium E10. Thus, the baseline gasoline includes 10 vol % ethanol, and we assume that the ethanol comes entirely from corn in that case. Note that the small variations in the refining GHG emissions shown in Figure 32 are included in Figure 33. However, the impacts of HOF market share and of vehicle efficiency gain are not included in Figure 33.

With regard to corn ethanol blending, E10, E25, and E40 HOF provide a 1%, 4%, and 9% GHG emissions reduction relative to baseline E10 gasoline, respectively. With regard to corn stover ethanol blending, the GHG emissions reduction due to E10, E25, and E40 HOF increase to 5%,

13%, and 24%, respectively, due to the lower GHG intensities of corn stover ethanol. The reductions result largely from the biogenic CO₂ credit from the use of bioethanol in the HOF.



(a) WTW GHG Emissions



(b) WTW Petroleum Use

Figure 32 WTW GHG emissions (g CO₂-e/MJ of HOF BOB) and petroleum use (MJ/MJ of HOF BOB) associated with BOB production for E10, E25, and E40 HOF in PADDs 2 and 3

The WTW petroleum use reduction due to ethanol blending results largely from the higher ethanol content in HOFs. Note that the differences in the WTW petroleum use between corn and corn stover ethanol blending are negligible, since both corn and corn stover are nonpetroleum sources. Also, it is important to note that the variations in the WTW results due to HOF scenarios (indicated by the error bars) are not significant, especially with regard to the WTW GHG emissions results.

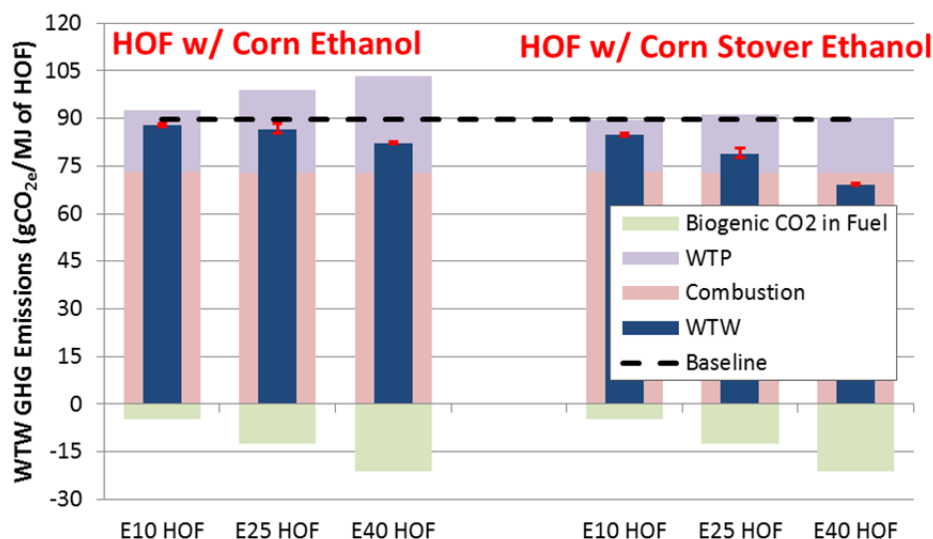


Figure 33 GHG emissions (g CO₂-e/MJ of HOF) associated with E10, E25, and E40 HOF in PADD 3

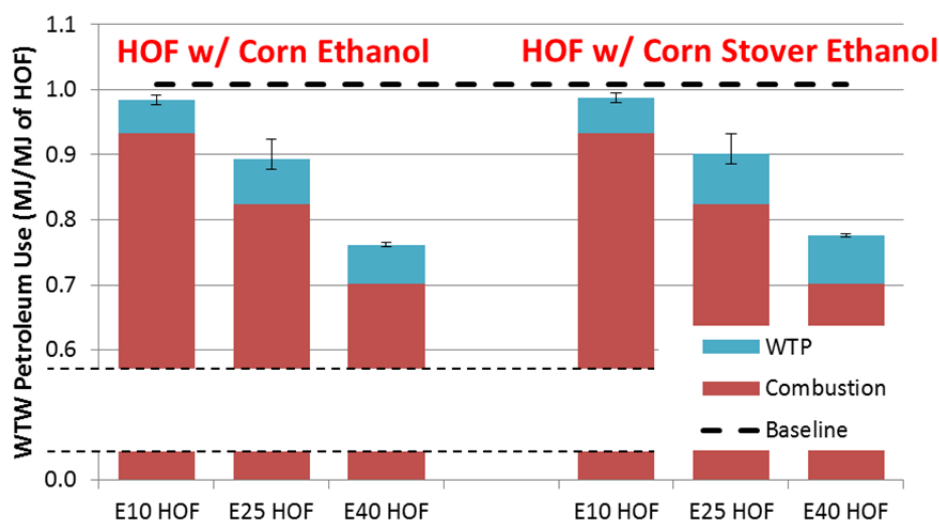


Figure 34 WTW petroleum use (MJ/MJ of HOF) associated with E10, E25, and E40 HOF in PADD 3

8.3. Additional Impacts of HOF Vehicle Efficiency Gains

Figure 35 presents GHG emissions in g CO₂-e per mile driven by HOFVs fueled with E10, E25, and E40 HOF blended with corn and corn stover ethanol in PADDs 2 and 3. Similarly, Figure 36 presents WTW petroleum use in MJ per mile driven by HOFVs fueled with E10, E25, and E40 HOF blended with corn and corn stover ethanol in PADDs 2 and 3. The baseline in the figures denotes the GHG emissions and WTW petroleum use per mile driven by gasoline internal combustion engine vehicles (ICEVs) fueled with business-as-usual E10 gasoline. As mentioned

earlier, a 5% MPGGE gain for HOFVs is assumed, while the E40 HOF maximum case considers a 10% MPGGE gain. Compared with the per-MJ results, the 5% and 10% MPGGE gains provide additional reductions in WTW GHG emissions and petroleum use of about 4% and 9%, respectively. With the additional GHG emissions benefits of HOFVs, the WTW GHG emissions reductions found in the E10, E25, and E40 HOF and E40 HOF maximum cases are estimated at 6%, 9%, 14%, and 18%, respectively, with corn ethanol. With corn stover ethanol, the WTW GHG emissions reductions increase to 9%, 17%, 27%, and 31%, respectively.

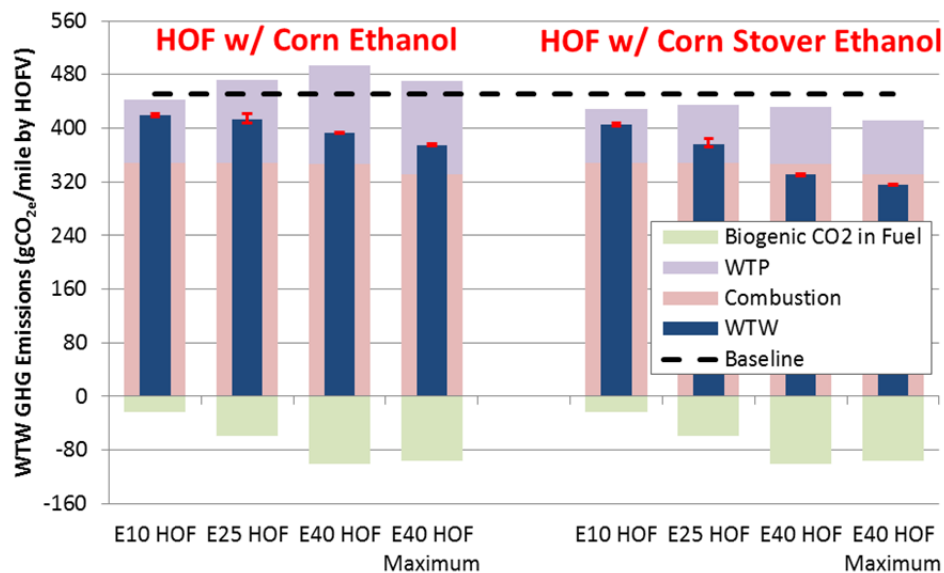


Figure 35 GHG emissions (g CO₂-e per mile driven) by HOFVs fueled with E10, E25, and E40 HOF in PADD 3

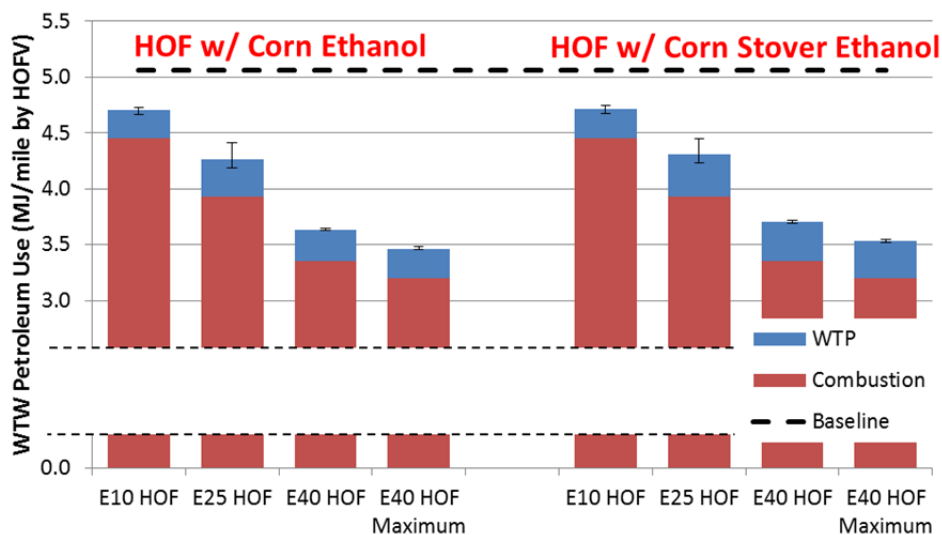


Figure 36 WTW petroleum use (MJ per mile driven) by HOFVs fueled with E10, E25, and E40 HOF in PADD 3

Figure 37 summarizes the impact of ethanol blending and MPGGE gain by HOF on the relative GHG emissions reduction to baseline vehicles. Note that the baseline for ethanol blending is regular (business-as-usual) E10 gasoline, while the baseline vehicle is the gasoline ICEV fueled by regular E10 gasoline (with corn as the feedstock for ethanol in E10). The error bars for the refinery impact indicate the maximum and minimum values of different HOF cases with different market shares averaging two PADD regions, three refinery configurations, and two seasons. As expected, the GHG emissions reduction due to ethanol blending increases with a higher ethanol blending level and is more significant with the use of corn stover ethanol than corn ethanol. For example, 40% corn stover ethanol blending can reduce the GHG emissions by 24% relative to those associated with baseline E10 gasoline. The 5% and 10% MPGGE gains result in additional GHG emissions reductions of about 4% and 8%, respectively, relative to baseline E10 vehicles, regardless of the ethanol feedstock and blending levels.



8.5. Impacts of HOF Market Shares

With HOF and HOFVs available, the U.S. total gasoline vehicle fleet will consume a mix of HOF and non-HOF regular gasoline. Also, at high penetrations of HOF and high ethanol blending levels (e.g., E25 and E40), the corn ethanol supply may not satisfy the demand for ethanol when ethanol demand exceeds 15 billion gallons a year. In such a case, we assume that the gasoline mix for the U.S. total gasoline vehicle fleet would consist of non-HOF regular E10 gasoline and HOF blended with corn and corn stover ethanol. Note that the share of non-HOF in the market will dilute the GHG emissions benefits of HOF, as shown in Figure 38.

Figure 38 shows the fleet average WTW GHG emissions (in g CO₂-e per mile driven) from the total gasoline (HOF and non-HOF) vehicle fleet in PADDs 2 and 3, with the aforementioned dilution effect. Similarly, Figure 39 shows the WTW petroleum gasoline (in MJ per mile driven) by the total gasoline vehicle fleet in PADDs 2 and 3. In these figures, we assume that the corn ethanol supply is limited to 15 billion gallons per year and that the balance is provided by cellulosic ethanol. This study uses corn stover ethanol as an example for cellulosic ethanol. When the HOF shares estimated by NREL's ADOPT model are used, the E10 HOF, E25 HOF, and E40 HOF cases can reduce the GHG emissions up to 3%, 10%, and 17% relative to the baseline case with the business-as-usual E10 regular gasoline. With the 10% MPGGE gain assumed in the E40 maximum case, the GHG emissions reduction grows to 20%. The maximum GHG emissions reduction can be achieved by HOF market shares of 65% for E25 and 70% for E40 in 2030, which requires 36 and 56 billion gallons of ethanol per year, respectively. It is beyond the scope of this study to determine if a supply of that amount of ethanol will be feasible in order to achieve the estimated maximum GHG emissions benefit from HOF.

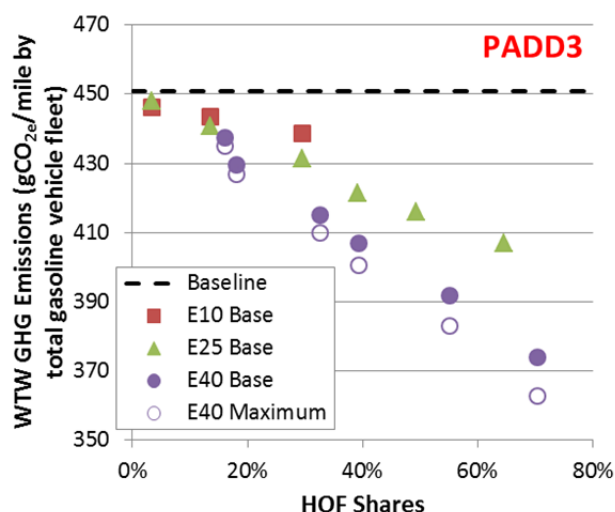


Figure 38 Fleet average WTW GHG emissions (g CO₂-e per mile driven) by total gasoline vehicle fleet in PADDs 2 and 3

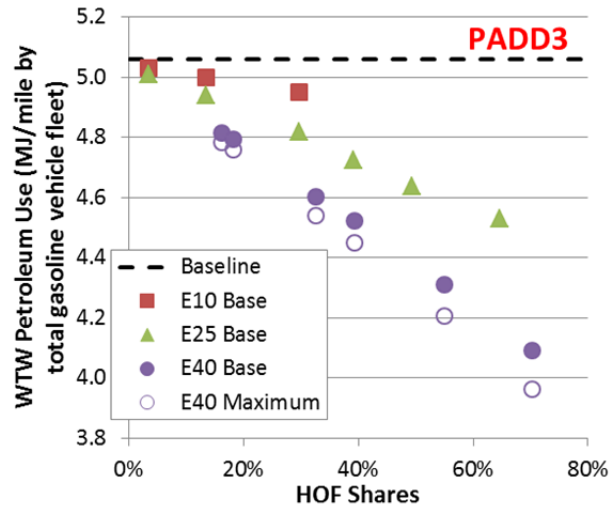


Figure 39 Fleet average WTW petroleum use (MJ per mile driven) by total gasoline vehicle fleet in PADDs 2 and 3

9. Limitations of This Study and Implications for Future Work

This study considered three “typical” refinery configurations in USGC and PADD 2. While the refinery configuration modeling provided insights into refineries’ responses to changes in supply and demand, it lacks the comprehensive evaluation afforded by aggregate modeling at the PADD level. Future analysis using aggregate models can provide additional insights into refining industry’s responses to variations in the quality of the crude supply and changes in the fuel quantity and quality demands in different PADDs.

This study considered a single crude slate based on EIA AEO projections for 2020. However, uncertainty exists regarding the crude supply, especially crude from Canadian oil sands and U.S. light crude. Further analysis of different crude slate scenarios with more heavy and/or light crude availability would provide insight into possible refinery operations with these different quality slates.

This study assumed no capital investment (e.g., reformers) in the refineries to produce HOF. This assumption limited the LP model’s ability not only to produce high market shares of E10 HOF but also to find solutions with RFG’s RVP constraints. Allowing capital expansion would provide insight into the cost of producing E10 HOF at large market shares and improve the reliability of E10 HOF results.

Prices were held constant throughout this study. Future work could further evaluate the impacts of domestic and export gasoline prices and their spread from ethanol prices. Furthermore, the model allowed unrestricted export of gasoline BOB without factoring in export market demands or prices. Further work to examine more constraints on gasoline exports, especially at high ethanol blending levels and large HOF market shares, would allow for a more rigorous assessment of the impacts of gasoline exports. Also, the cost of an infrastructure hat is carrying additional BOB needs to be taken into account.

As discussed above, the fuel economy of baseline regular E10 vehicles from the ADOPT model is relatively low compared to other projections (e.g., EIA’s Annual Energy Outlook) and does not improve significantly. This slow improvement in vehicle efficiency requires further investigation.

10. Conclusions

In this study, we evaluated the impacts of producing HOF with a RON of 100, using a range of ethanol blending levels (E10, E25, and E40), vehicle efficiency gains, and HOF market penetration scenarios (3.4% to 70%), on WTW petroleum use and GHG emissions. In particular, we conducted LP modeling of petroleum refineries to examine the impacts of different HOF production scenarios on petroleum refining energy use and GHG emissions. We compared two cases of HOF vehicle fuel economy gains of 5% and 10% in terms of MPGGE to baseline regular gasoline vehicles. We incorporated three key factors in GREET — (1) refining energy intensities of gasoline components for the various ethanol blending options and market shares, (2) vehicle efficiency gains, and (3) upstream energy use and emissions associated with the production of different crude types and ethanol — to compare the WTW GHG emissions of various HOF/vehicle scenarios with the business-as-usual baseline regular gasoline (87 AKI E10) pathway.

We found that the impacts from introducing HOF on reducing WTW GHG emissions were dominated by vehicle efficiency gains that resulted from the use of HOF and ethanol blending levels, while the production efficiency of gasoline BOB for various HOF blend levels (E10, E25, and E40) had only a small impact on WTW GHG emissions. The 5% and 10% MPGGE fuel economy gains helped reduce WTW GHG emissions by 4% and 8%, respectively, relative to baseline E10 gasoline. The additional WTW GHG emission reductions from corn ethanol blending were 5% and 10% for E25 and E40, respectively. As a result, when the corn ethanol was used for blending, total WTW GHG emission reductions from using E10, E25, and E40 relative to baseline E10 gasoline were 5%, 10% and 15%, respectively, with a 5% MPGGE gain. Using E40 achieved an 18% total WTW GHG emission reduction, with a 10% MPGGE gain. When corn stover ethanol was used for blending, the additional WTW GHG reductions were 12% and 24% for E25 and E40, respectively. As a result, when the corn stover ethanol was used, total WTW GHG emission reductions from using E10, E25, and E40 relative to baseline E10 gasoline were 8%, 18%, and 28%, with a 5% MPGGE gain. Using E40 achieved a 32% total WTW GHG emission reduction, with a 10% MPGGE gain. The WTW analysis shows that ethanol can be a major enabler in producing HOF and result in additional reductions in WTW GHG emissions when compared to regular E10 gasoline.

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Appendix A: PADD2 Charts

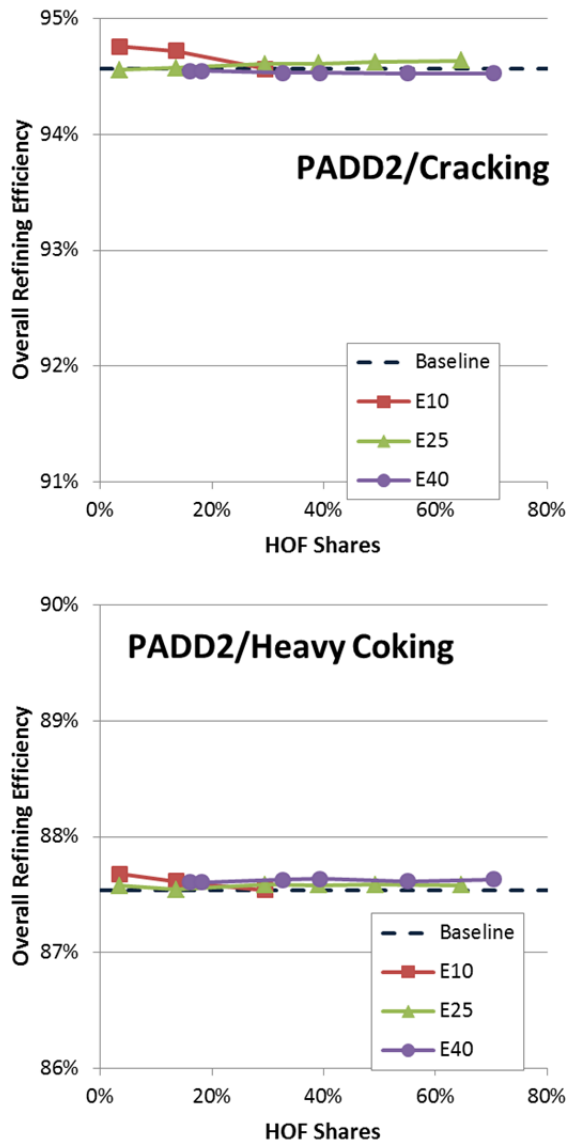


Figure A1 Overall refining efficiency versus HOF share cases for each refinery configuration in PADD 2

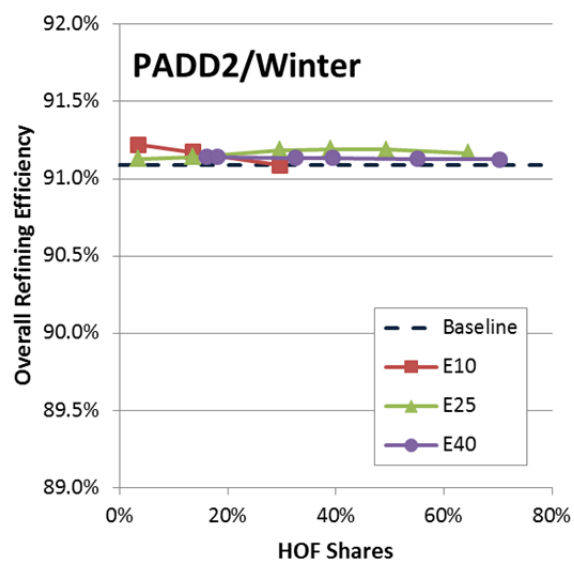


Figure A2 Overall refining efficiency versus HOF shares for summer and winter in PADD 2

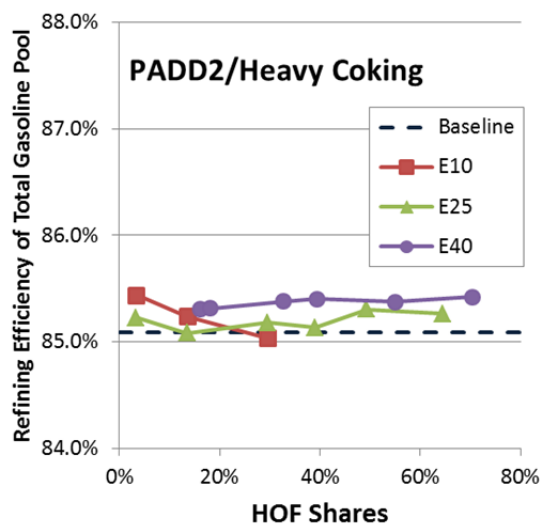
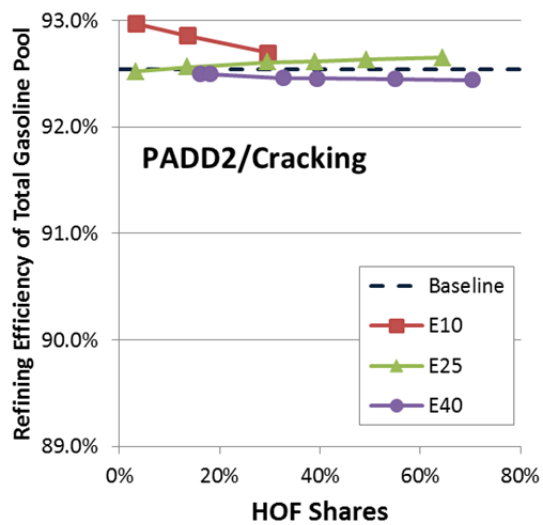


Figure A3 Refining efficiency of total gasoline pool versus HOF shares for each refinery configuration in PADD 2

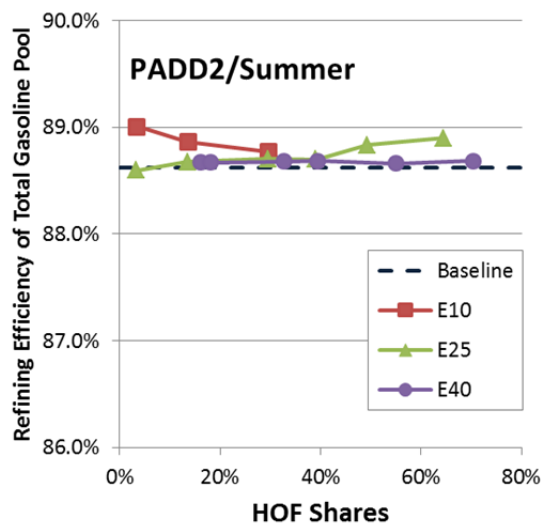


Figure A4 Refining efficiency of total gasoline pool versus HOF shares for summer and winter in PADD 2

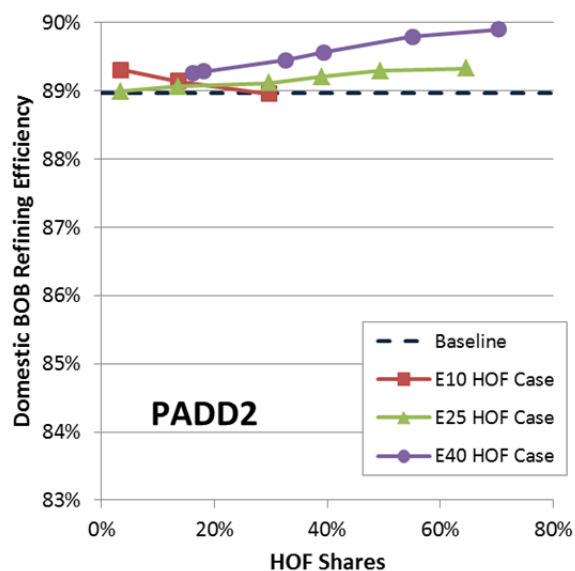


Figure A5 Refining efficiency of domestic BOB and export gasoline versus HOF shares in PADD 2

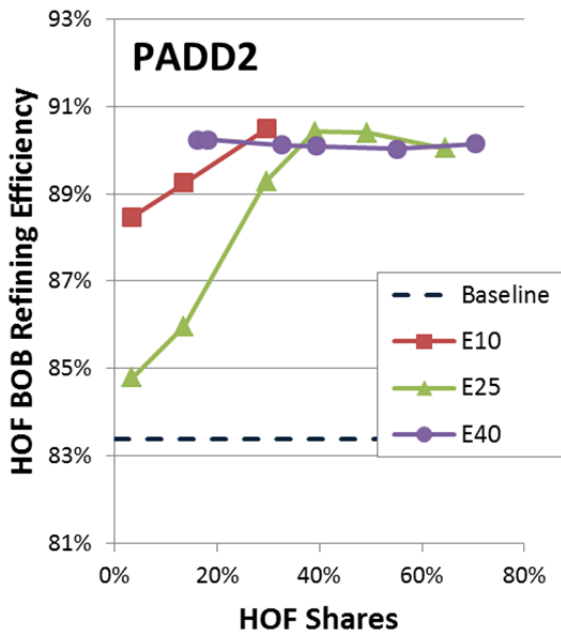


Figure A6 Refining efficiency of HOF and regular BOB versus HOF shares in PADD 2

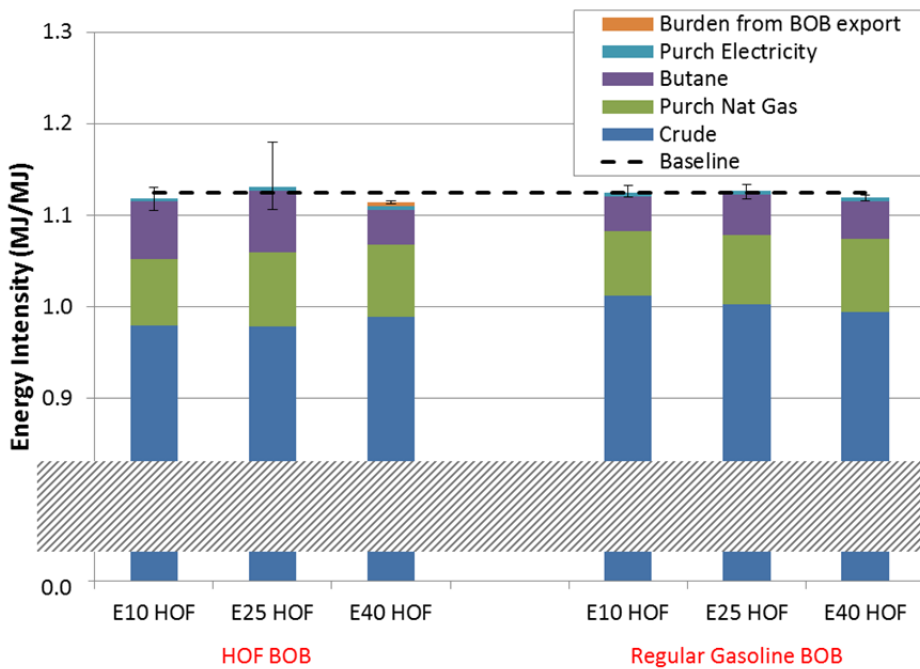


Figure A7 Energy intensities of gasoline BOBs for the E10 HOF, E25 HOF, and E40 HOF cases in PADD 2

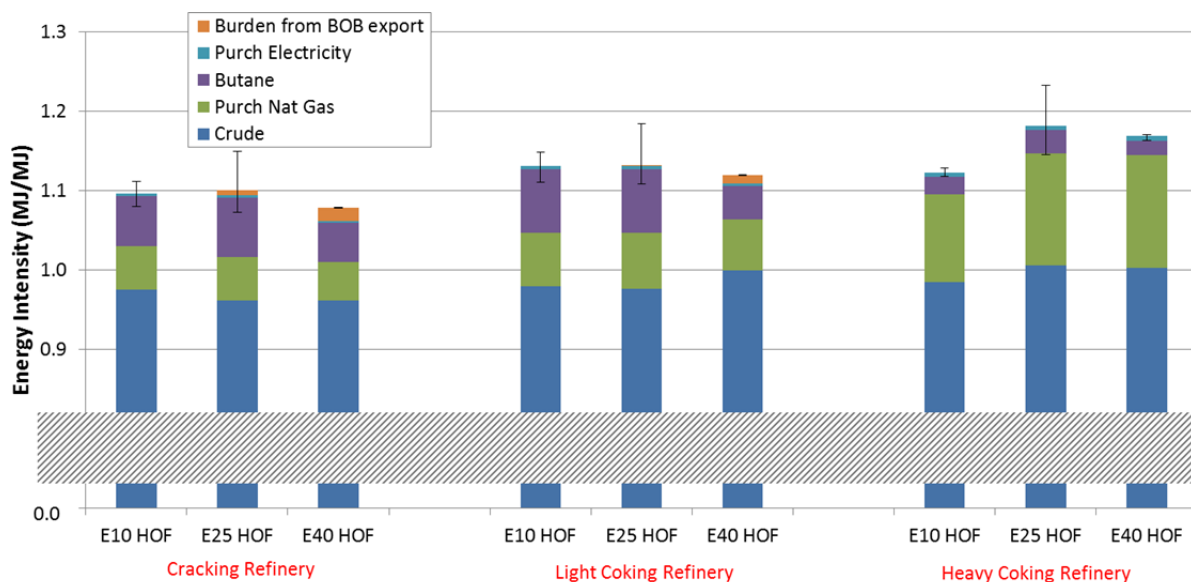


Figure A8 Energy intensities of gasoline BOBs for the E10 HOF, E25 HOF, and E40 HOF cases by refinery configuration in PADD 2

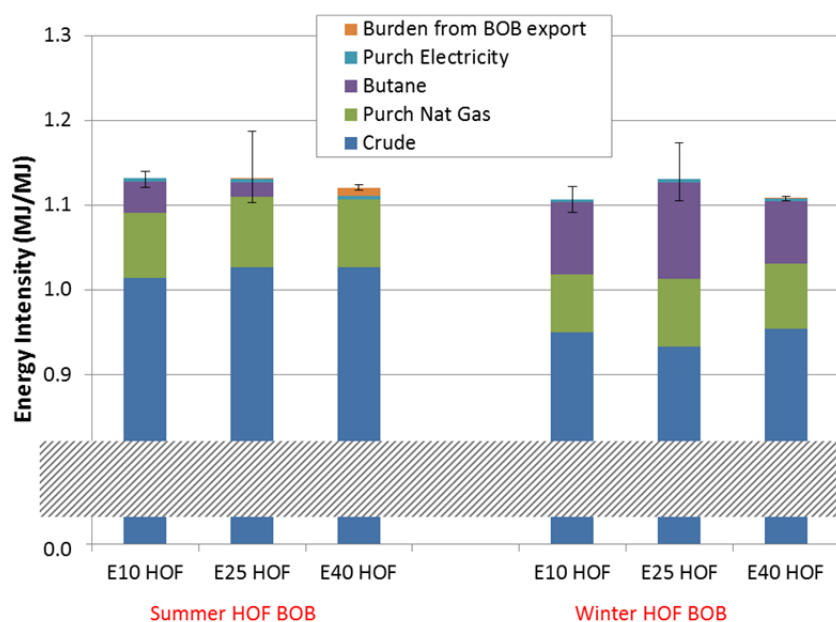


Figure A9 Energy intensities of gasoline BOBs for the E10 HOF, E25 HOF, and E40 HOF cases by season in PADD 2

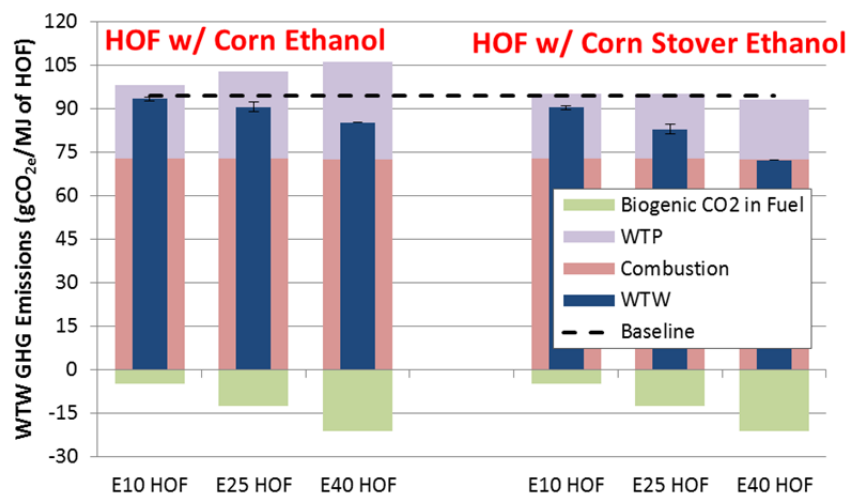


Figure A10 GHG emissions (gCO₂-e/MJ of HOF) associated with E10, E25, and E40 HOF in PADD 2

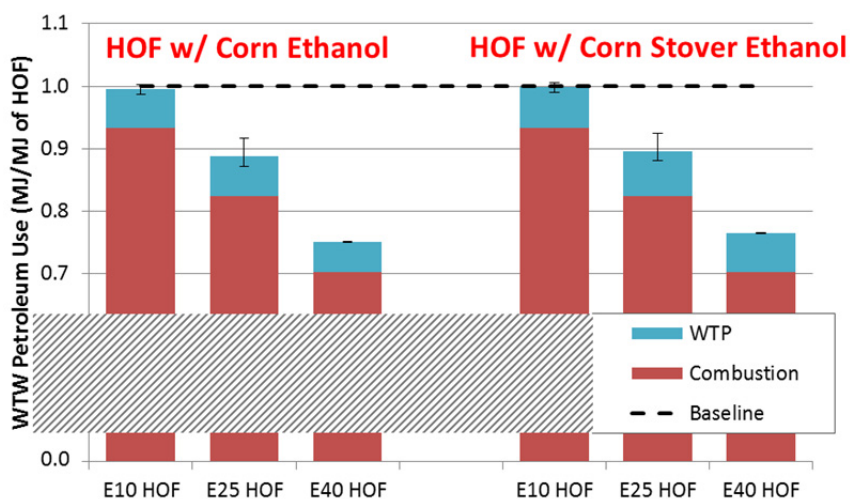


Figure A11 WTW petroleum use (MJ/MJ of HOF) associated with E10, E25, and E40 HOF in PADD 2

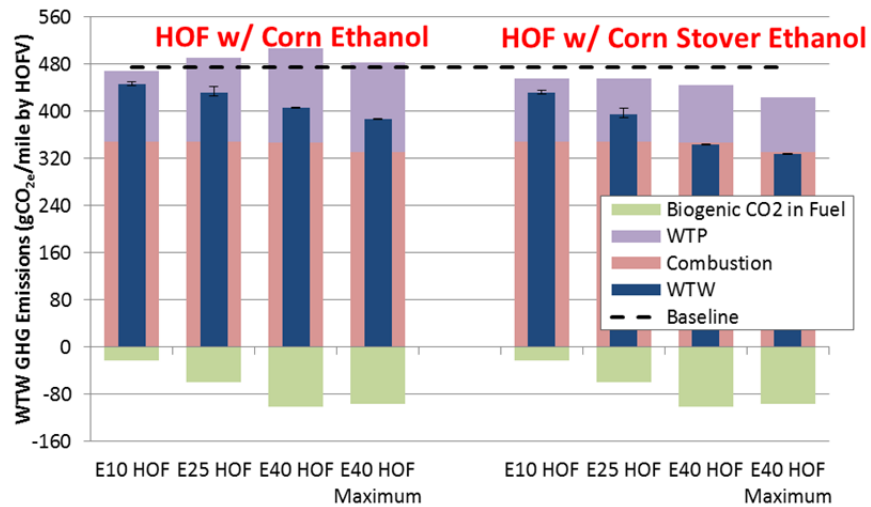


Figure A12 GHG emissions (gCO₂-e per mile driven) by HOFV fueled with E10, E25, and E40 HOF in PADD 2

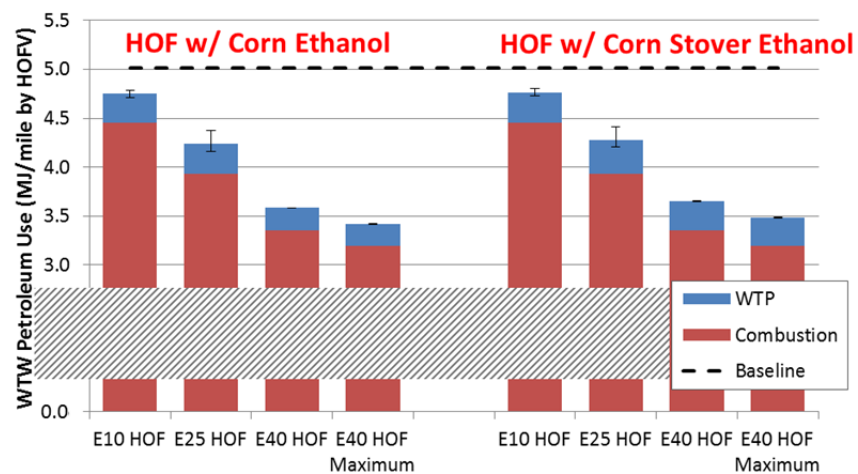


Figure A13 WTW petroleum use (MJ per mile driven) by HOFV fueled with E10, E25, and E40 HOF in PADD 2

Appendix B: Key LP Run Results

Table B1 Refinery LP Run Results: Inputs and Outputs

	Blending Level				Refinery Configuration		Season	Region
LOCATION	PADD 3	PADD 3	PADD 3	PADD 3	PADD 3	PADD 3	PADD 3	PADD 2
CONFIGURATION	LTCOK	LTCOK	LTCOK	LTCOK	CRK	HVYCOK	LTCOK	LTCOK
SEASON	Summer	Summer	Summer	Summer	Summer	Summer	Winter	Summer
HOF ETHANOL BLENDING	E25	N/A	E10	E40	E25	E25	E25	E25
HOF SHARES (%)	29.6	0.0	29.6	32.6	29.6	29.6	29.6	29.6
Inputs								
Crude Oil (MBPD)	5,300	5,300	5,300	5,300	740	1,400	5,300	1,670
API	30.9	30.9	30.9	30.9	42.4	25.9	30.9	29.8
Sulfur	2.0	2.0	2.0	2.0	0.4	2.8	2.0	1.8
Other Inputs (MBPD)								
Butane	0	0	0	0	0	0	72	0
Isobutane	70	71	64	64	2	3	62	18
Ethanol	370	246	240	499	30	93	369	126
Purchased Energy								
Natural Gas (FOE MBPD)	251	257	232	267	17	122	256	79
Electricity (10 ⁶ kWh/D)	26	26	25	26	2	11	26	8
Products (MBPD)								
Butane	105	96	103	96	13	29	0	19
Isobutane	0	0	0	0	0	0	0	0
Propane	45	42	58	43	9	19	48	13
Propylene	196	196	196	177	18	42	177	56
Total Finished Gasoline:	2,557	2,447	2,389	2,687	301	641	2,708	871
Total USA Non-HOF:	1,799	2,447	1,682	1,697	144	451	1,796	613
Conventional	1,439	1,957	1,345	1,358	144	361	1,437	491
RFG	360	489	336	339	0	90	359	123
Total USA HOF:	756	0	707	821	61	190	755	258
Conventional	605	0	566	657	61	152	604	206
RFG	151	0	141	164	0	38	151	52
Total Finished Exports	2	0	0	169	97	0	157	0
Distillate	2,699	2,699	2,699	2,731	351	724	2,731	813
Jet Fuel	424	424	424	424	90	112	424	200
Ultra Low Sulfur Diesel	2,275	2,275	2,275	2,307	261	612	2,307	613
Residual Fuel Oil	0	0	0	0	81	0	0	0
Coke (10 ³ Ton/D)	67	67	67	68	0	27	68	21
Sulfur (10 ³ Ton/D)	12	12	12	12	0	5	12	3
Summary (MBPD)								
Total C3+: Input	5,740	5,617	5,604	5,863	772	1,496	5,803	1,814
Total C3+: Output	5,601	5,481	5,444	5,734	774	1,454	5,664	1,773
Total C3+: Gain	-138	-136	-160	-128	2	-42	-139	-41
Total C5+: Excluding ethanol	4,886	4,900	4,848	4,919	704	1,272	5,070	1,558

Table B2 Refinery LP Run Results: Throughput and Characteristics of Key Process Units

	Blending Level				Refinery Configuration		Season	Region
LOCATION	PADD 3	PADD 3	PADD 3	PADD 3	PADD 3	PADD 3	PADD 3	PADD 2
CONFIGURATION	LTCOK	LTCOK	LTCOK	LTCOK	CRK	HVYCOK	LTCOK	LTCOK
SEASON	Summer	Summer	Summer	Summer	Summer	Summer	Winter	Summer
ETHANOL BLENDING	E25	N/A	E10	E40	E25	E25	E25	E25
HOF SHARES (%)	29.6	0.0	29.6	32.6	29.6	29.6	29.6	29.6
Reformer	947	947	891	934	139	265	950	322
Severity	93.7	91.5	101.0	90.0	95.6	93.8	93.7	94.8
Reforming*Severity (MMBPD)	88.7	86.6	90.0	84.1	13.3	24.9	89.1	30.5
Isomerization	106	106	106	106	22	28	106	33
ULSD Hydrotreating	2,272	2,273	2,273	2,304	260	439	2,304	613
FCC	1,535	1,535	1,535	1,539	156	288	1,539	508
FCC Yield (vol %)								
FCC Naphtha	58	58	58	57	61	60	57	57
FCC C4 Olefins	9.8	9.8	9.8	9.1	10.6	10.4	9.1	9.0
Light Cycle Oil + Slurry	25.4	25.4	25.4	27.9	20.0	23.6	27.9	28.8
Alkylation	286	286	286	266	29	60	266	87
Hydrogen Plant	1,358	1,410	1,266	1,491	0	939	1,394	399

Table B3 Refinery LP Run Results: Gasoline BOB Pool Composition (vol) and Octane Barrel

	Blending Level				Refinery Configuration		Season	Region
LOCATION	PADD 3	PADD 3	PADD 3	PADD 3	PADD 3	PADD 3	PADD 3	PADD 2
CONFIGURATION	LTCOK	LTCOK	LTCOK	LTCOK	CRK	HVYCOK	LTCOK	LTCOK
SEASON	Summer	Summer	Summer	Summer	Summer	Summer	Winter	Summer
ETHANOL BLENDING	E25	N/A	E10	E40	E25	E25	E25	E25
HOF SHARES (%)	29.6	0.0	29.6	32.6	29.6	29.6	29.6	29.6
Non-HOF BOB (MBPD)	1,627	2,213	1,521	1,535	130	408	1,624	555
Alkyate Pool	7%	16%	16%	12%	0%	3%	5%	15%
Total Reformate	34%	33%	13%	39%	46%	45%	31%	23%
FCC Gasoline	40%	29%	49%	33%	25%	25%	49%	41%
C5/C6 Isomerase	7%	12%	5%	7%	17%	7%	2%	6%
Naphtha	13%	9%	17%	9%	12%	20%	13%	15%
HOF BOB (MBPD)	567	0	636	493	45	142	566	193
Alkyate Pool	33%	N/A	8%	0%	0%	34%	26%	2%
Total Reformate	49%	N/A	86%	51%	72%	33%	74%	88%
FCC Gasoline	18%	N/A	0%	35%	28%	33%	0%	10%
C5/C6 Isomerase	0%	N/A	6%	0%	0%	0%	0%	0%
Naphtha	0%	N/A	0%	14%	0%	0%	0%	0%
Refinery RON x MMBPD	197	198	197	194	25	49	211	67
Ethanol RON x MMBPD	44	29	28	60	4	11	44	15
Gasoline RON x MMBPD	242	227	226	254	28	61	255	82



Energy Systems Division

9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4854

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