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Well-to-Wheels Greenhouse Gas Emission Analysis of High-Octane Fuels with Ethanol Blending: Phase II Analysis with Refinery Investment Options

Energy Systems Division

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Well-to-Wheels Greenhouse Gas Emission Analysis of High-Octane Fuels with Ethanol Blending: Phase II Analysis with Refinery Investment Options

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Notation

ADOPT	Automotive Deployment Options Projection Tool
AEO	Annual Energy Outlook
AKI	anti-knock index
API	American Petroleum Institute
BOB	blendstock for oxygenate blending
CA	California
CCR	continuous catalytic reformers
CG	conventional gasoline
CO_2	carbon dioxide
CO_2e	CO_2-equivalent
cpg	cents per gallon
DI	driveability index
DVPE	dry vapor pressure equivalent
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FCC	fluidized catalytic cracking
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HF	hydrofluoric
HOF	high-octane fuel
HOFV	high-octane fuel vehicle
kBPD	thousand barrels per day
LHV	lower heating value
LP	linear programming
LPG	liquefied petroleum gas
LTO	light tight oil
MBPD	million barrels per day
MIT	Massachusetts Institute of Technology
MON	motor octane number
mpg	miles per gallon
mpgge	miles per gasoline gallon equivalent
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
OSBL	outside battery limit
PADD	Petroleum Administration for Defense District
RFG	reformulated gasoline

ROI	return on investment
RON	research octane number
RVP	Reid vapor pressure
SRR	semi-regenerative catalytic reformer
USGC	U.S. Gulf Coast
WTW	well-to-wheels

Executive Summary

Higher-octane gasoline can enable increases in an internal combustion engine's energy efficiency and a vehicle's fuel economy by allowing an increase in the engine compression ratio and/or by enabling downspeeding and downsizing. Producing high-octane fuel (HOF) with the current level of ethanol blending (E10) could increase the energy and greenhouse gas (GHG) emissions intensity of the fuel product from refinery operations. Alternatively, increasing the ethanol blending level in final gasoline products could be a promising solution to HOF production because of the high octane rating and potentially low blended Reid vapor pressure (RVP) of ethanol at 25% and higher of the ethanol blending level by volume. In our previous HOF well-to-wheels (WTW) report (the so-called phase I report of the HOF WTW analysis), we conducted WTW analysis of HOF with different ethanol blending levels (i.e., E10, E25, and E40) and a range of vehicle efficiency gains with detailed petroleum refinery linear programming (LP) modeling by Jacobs Consultancy and showed that the overall WTW GHG emission changes associated with HOFVs were dominated by the positive impact associated with vehicle efficiency gains and ethanol blending levels, while the refining operations to produce gasoline blendstock for oxygenate blending (BOB) for various HOF blend levels had a much smaller impact on WTW GHG emissions (Han et al. 2015).

The scope of the previous phase I study, however, was limited to evaluating PADDs 2 and 3 operation changes with various HOF market share scenarios and ethanol blending levels. Also, the study used three typical configuration models of refineries (cracking, light coking, and heavy coking) in each PADD, which may not be representative of the aggregate response of all refineries in each PADD to various ethanol blending levels and HOF market scenarios. Lastly, the phase I study assumed no new refinery expansion in the existing refineries, which limited E10 HOF production to the volume achievable by the cracking refinery configuration. To be able to satisfy large market demands of E10 HOF, that study arbitrarily relaxed the RVP requirements by replacing reformulated gasoline (RFG) RVP requirement of 7 psi in summer with conventional gasoline (CG) RVP requirement of 9 psi in summer. To examine the response by all refineries in major refinery regions, this phase II of the HOF WTW analysis employed regionally aggregated refinery models for the following six regions: PADDs 1, 2, 3, 4, and 5 excluding California (CA) and CA separately. Using aggregate refinery models, this phase II study examined the impacts of ethanol blending and HOF market shares on the refinery operations in these six regions. Also, this study included refinery expansion to produce a pre-determined HOF volume with 10% ethanol blending. In particular, this study examined several refinery expansion options using refinery configuration models to investigate a practical refinery response to the increase in E10 HOF market demand.

Figure ES.1 summarizes the GHG emission reductions of HOF vehicles (HOFVs) from miles per gallon of gasoline-equivalent (mpgge) gains of 5 and 10%, ethanol blending, and changes in refinery operation with HOF production estimated in this phase II study. Note that 5 and 10% MPGGE gains are assumed for illustrative purposes from literature studies as representative of the broad magnitude of fuel economy gains expected for higher octane. The results show that the impacts of HOF introduction on WTW GHG emissions were dominated by vehicle efficiency gains resulting from the use of HOF and ethanol blending levels. The 5 and 10% mpgge gains by HOFVs reduced the WTW GHG emissions by 4 and 8%, respectively, relative to baseline E10 gasoline vehicles. Additional 4 and 9% reductions in WTW GHG emissions can be realized with E25 and E40 blending of corn ethanol, respectively (corn ethanol GHG reductions were simulated with the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation [GREET®] Model). With corn stover ethanol blending, the additional WTW GHG reductions were 2, 12, and 23% for E10, E25, and E40, respectively. On the other hand, the production efficiencies of gasoline BOB for various HOF blend levels (E10, E25, and E40) had only a small impact on WTW GHG emissions (~1%). The WTW analysis shows that ethanol can be a major enabler in producing HOF and can result in additional reductions in WTW GHG emissions compared with regular E10 gasoline. Note that these results from aggregated refinery LP models were generally consistent with those from configuration refinery LP models in phase I of this HOF WTW analysis.

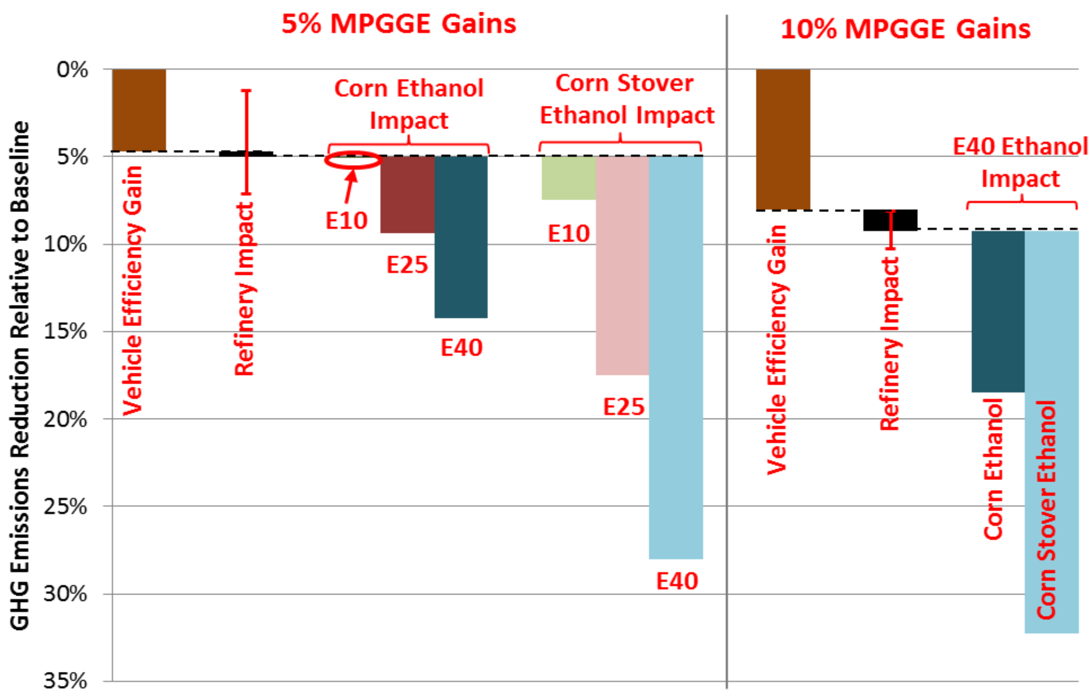


Figure ES.1 HOF-fueled vehicle WTW GHG emission reductions relative to emissions of vehicles fueled with regular gasoline (E10) on per mile basis

Additionally, our regional WTW analysis showed that the WTW GHG emission reductions by HOFVs fueled with E25 HOF relative to regular gasoline vehicles in the non-HOF scenario are fairly consistent throughout all regions—from 36 to 40 grams CO_2 equivalent per mile driven (g CO_2/mile driven)—as shown in Figure ES.2. The reduction in the WTW GHG emissions is driven largely by the low GHG emissions associated with ethanol blendstock and the 5% vehicle efficiency gain. In the figure, corn ethanol is used for ethanol blending. The key driver for the regional differences in the WTW GHG emissions is the crude source, in addition to gasoline refining efficiency. For example, the WTW GHG emissions of PADDs 2 and 4, in which a large amount of Canadian oil sands is consumed, are greater than those of PADDs 1, 3, and 5 without CA. The WTW GHG emissions of E25 HOF in CA are higher than those in the other regions because of the low refining efficiency in the former.

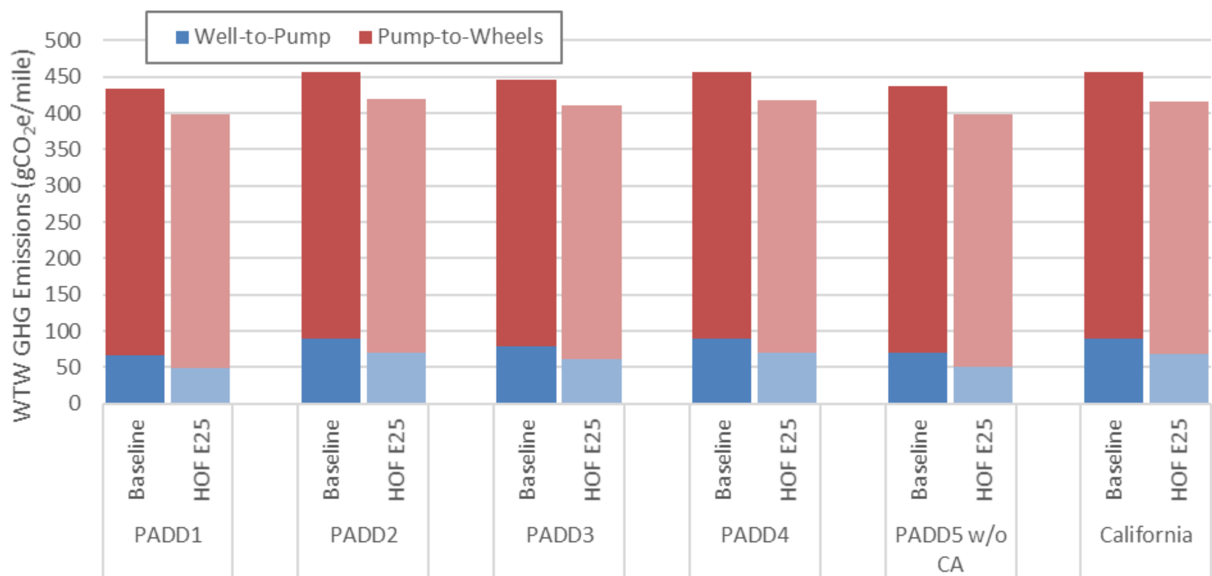


Figure ES.2 WTW GHG emissions (g CO_2e/mile driven) by HOFVs fueled with E25 HOF as compared with regular gasoline vehicles in the non-HOF baseline scenario by region (corn ethanol is assumed for ethanol blendstock)

Phase I of this HOF WTW analysis showed that, without the use of higher-ethanol blends, such as E25 and E40, petroleum refineries would face significant difficulties to meet the high demand for HOF when HOF market penetration is significant (e.g., over 25%) because of the tight constraints on RON and RVP. In particular, refineries with low complexity have a limited ability to produce a significant amount of high-RON and low-RVP blendstock. Thus, to increase the octane level in the overall fuel using E10 alone, refinery expansion of processing units needs to be considered. To address the WTW GHG emissions impacts and associated costs, this phase II study examined several refinery expansion options for two bookend configuration models (high- and low-octane refineries) for U.S. Gulf Coast medium coking refineries. In the high-octane configuration, a continuous catalytic reformer (CCR) is combined with an isomerization unit and a sulfuric acid alkylation unit. For the low-octane configuration, a semi-regenerative catalytic reformer (SRR) is combined with a hydrofluoric acid alkylation unit (no isomerization unit is used). Due to the initial processing capacities, it is easier for the high-octane refinery to produce a large volume of HOF than it is for the low-octane refinery.

Refinery expansion options included (1) an outside battery limit (OSBL) improvement (storage, blending, and piping systems expansion) for more selective and advanced blending, (2) the addition of an isomerization unit in addition to an OSBL improvement (OSBL+ISOM), (3) the expansion of an alkylation unit in addition to an OSBL improvement (OSBL+ALK), and (4) the upgrading of a reformer from SRR to CCR in addition to an OBSL improvement (OSBL+CCR). Note that one of the key benefits of the OSBL improvement assumed in this study is the splitting and segregation of light and heavy reformate in the different gasoline pools. The capability to segregate and optimize the blending of these two streams in the HOF and non-HOF pools is an important operational strategy at high E10 HOF volumes. Figure ES.3 shows the WTW GHG emissions of regular gasoline BOB and E10 HOF BOB in g CO_2e/MJ BOB as well as the HOF market shares for the refinery expansion options. Note that the results are on a MJ-BOB basis, which focus on the petroleum refining impacts and do not take into account the vehicle efficiency gains nor the low GHG emissions intensity of blended ethanol. Because the high-octane refinery has an isomerization unit and CCR in the base scenario, OSBL+ISOM and OSBL+CCR are considered only for the low-octane refinery.

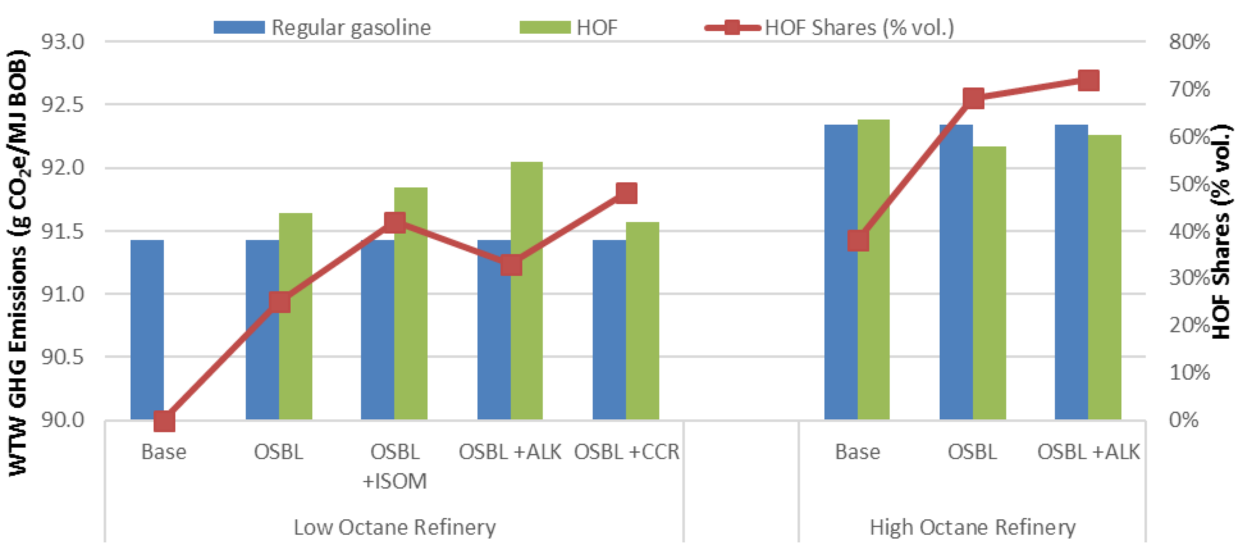


Figure ES.3 WTW GHG emissions of regular gasoline BOB and E10 HOF BOB (g CO_2e/MJ BOB) and HOF market shares (% volume) for refinery expansion options

In the low-octane refinery, the OBSL improvement increases the total HOF production share from 0% to 25%, while it increases the total HOF production share in the high-octane refinery from 38% to 68%. For the low-octane refinery, OSBL+ISOM, OSBL+ALK, and OSBL+CCR increase the total HOF production share to 42, 33, and 48%, respectively. For these refinery expansion options, only OSBL+ISOM can meet the RFG share requirement (20% of HOF RFG in total HOF). In particular, while OSBL+CCR increases the HOF production share most significantly, it produces less than 1% of HOF RFG in total HOF because a large share of heavy reformate makes gasoline too heavy to meet the driveability index (DI) specification. For the high-octane refinery, the HOF production share increases to 72% by OSBL+ALK.

In Figure ES.3, the WTW GHG emissions of regular gasoline BOB and E10 HOF BOB were adjusted to take into account the incremental WTW GHG emissions of regular gasoline BOB for each option relative to the base option. Thus, the WTW GHG emissions of regular gasoline BOB are consistent throughout the refinery expansion options at 91.4 and 92.3 g CO_2e/MJ BOB for the low- and high-octane refineries, respectively. Overall, the impact of the refinery expansion options on the adjusted WTW GHG emissions of HOF BOB with the adjustment are not significant, less than 0.6 and 0.2 g CO_2e/MJ BOB for the low- and high-octane refineries, respectively. However, it is important to note that the small increases in the WTW GHG emissions of E10 HOF BOB with refinery expansions are valid under specific conditions and at limited HOF penetration. Thus, these results can neither be extrapolated to nor directly compared with the results from studies that assume higher HOF penetrations, such as Hirshfeld et al. (2014).

These refinery expansion options are associated with increases in the cost of gasoline products. To estimate the costs associated with increased HOF production, this study examined the incremental capital and fixed costs in the OSBL and the OSBL+ISOM options. Amortizing this cost depends on the financial parameter assumptions. With two cases chosen in this study (5% and 10% return on investment after tax), the cost of the OSBL improvement for more selective blending is approximately 0.4 cents per gallon (cpg) of total gasoline or less. If isomerization is chosen in addition to the OSBL improvement, this cost ranges from 1.6 to 2.2 cpg of total gasoline.

In summary, increasing ethanol blending level from 10% to 25% and 40% enables refineries to meet a large demand of 100-RON HOF without refinery expansions. Moreover, HOFVs fueled with E25 and E40 HOF can achieve large reductions of GHG emissions relative to baseline vehicles fuels using regular E10 gasoline. The GHG emissions reductions are largely caused by the vehicle efficiency gains with the use of HOF and the increased blending level of ethanol with lower GHG emission intensities than gasoline. With the current level of ethanol blending at

10%, however, this study showed that the refineries would require a refinery expansion, such as an OSBL improvement for more selective blending, to meet a large increase in demand for HOF at an aggregated level. Note that the reformer severity and throughput in the E10 HOF scenarios were significantly higher than those in the baseline and E25 and E40 HOF scenarios, which suggested substantial challenges to meet the increased octane demand by E10 HOF. Note also that while the refineries at an aggregated level can meet the demand, the individual refineries could have different responses and challenges to the increased HOF demand. For example, our detailed investigation on refinery expansion options to increase the HOF production using two refinery configuration models (low- and high-octane refineries) showed that OSBL+ISOM could be a promising solution for the low octane refinery to a large volume of E10 HOF production, while the HOF share is still limited to 42% of total gasoline. Moreover, this study showed that DI is also an important fuel specification for E10 HOF in addition to RON and RVP, since HOF can be too heavy (or T50, T70, and T90 [the temperatures for the evaporated percentages of 50, 70, and 90%, respectively] of HOF can be too high) with a high share of heavy reformate.

1. Introduction

Higher-octane gasoline allows different engine designs (such as high-compression and downsped and downsized engines) to improve an internal combustion engine's energy efficiency and thus a vehicle's fuel economy. Leone et al. (2015) reported that, as the engine's compression ratio increases from 10:1 to 12:1 and 13:1, the vehicle energy efficiency could be increased by 5–7 and 6–9%, respectively. Leone et al. (2015) also observed that the increase of 2.5 to 6 points in the fuel's research octane number (RON) would be required to increase the compression ratio by 1 point (e.g., from 10:1 to 11:1), depending on cylinder displacement and geometry and engine technology (e.g., direct injection, turbocharging, and advanced spark control).

Production of high-octane fuel (HOF) requires changes in refinery operation, which may increase the energy and greenhouse gas (GHG) emission intensity of the fuel product. Alternatively, a promising solution to HOF production is to increase the ethanol blend level in final gasoline products, since ethanol provides a significant octane boost, while the blended Reid vapor pressure (RVP) of gasoline products decreases with increased ethanol blending beyond 10% ethanol by volume. Moreover, increasing HOF production with a higher ethanol blending level provides an additional opportunity for further increasing the compression ratio due to ethanol's high latent heat of vaporization, which provides charge cooling benefits to antiknock resistance (Sluder et al. 2016; Thomas et al. 2015). A study by original equipment manufacturers (OEMs) of U.S. automobiles examined the impact of increasing gasoline RON from 93.2 to 95, 98, 100, and 102 with different ethanol blending levels (E10, E20, and E30), and showed that higher ethanol blending levels reduce the petroleum refining cost and GHG emissions (Hirshfeld et al. 2014). For example, with 98 RON, the increase of ethanol blending level from E10 to E20 and E30 reduces incremental refining cost from 20 to 6 to 2 cents per gallon (cpg), respectively, while changes in refinery carbon dioxide (CO_2) intensities in grams per megajoule (g/MJ) of gasoline relative to E10 gasoline with 93.2 RON is reduced from +7 to -4 to -12%. The OEM study focused only on the economics and CO_2 emissions of refinery operation and did not conduct a well-to-wheels (WTW) analysis.

A Massachusetts Institute of Technology (MIT) study showed that the increase in the market share of HOF with 98 RON could reduce annual U.S. gasoline consumption by 3.0−4.4% via improved vehicle efficiency, resulting in a net CO_2 emission reduction of 19−35 million tonnes per year by 2040 and other cost savings (Speth et al. 2014). The MIT study evaluated the ethanol blending levels of up to 20% by volume (E10, E15, and E20). The focus of these studies was mainly on CO_2 emissions, the cost of producing HOF, and the associated vehicle efficiency improvements. While the MIT study estimated the impact of HOF production on annual lifecycle CO_2 emissions by a light-duty vehicle fleet, it neither estimated the GHG emissions associated with individual refined products nor provided detailed insights into refinery responses to HOF production. Thus, further WTW analysis of HOF gasoline in the United States is warranted to estimate the GHG emissions associated with HOF and to understand the responses by refineries.

Argonne National Laboratory has conducted a WTW analysis of HOF with different ethanol blending levels with detailed petroleum refinery linear programming (LP) modeling by Jacobs Consultancy. The net change in GHG emissions associated with HOF vehicles (HOFVs), simulated in early LP modeling and WTW analysis, was documented in the previous, HOF WTW phase I report (Han et al. 2015; Theiss et al. 2016) for various HOF (100-RON) gasoline production options (i.e., E10, E25, and E40) and a range of vehicle efficiency gains.

The phase I WTW analysis covered all lifecycle stages of HOF, including crude recovery and refining, ethanol production, and vehicle operation. To assess HOF production impacts on refinery operations, the study used a LP model to simulate three major petroleum refinery configurations (cracking, light coking and heavy coking) in the two largest Petroleum Administration for Defense Districts (PADDs 2 and 3) shown in Figure 1. The LP results were further analyzed to allocate refinery energy use and GHG emissions to various refined products

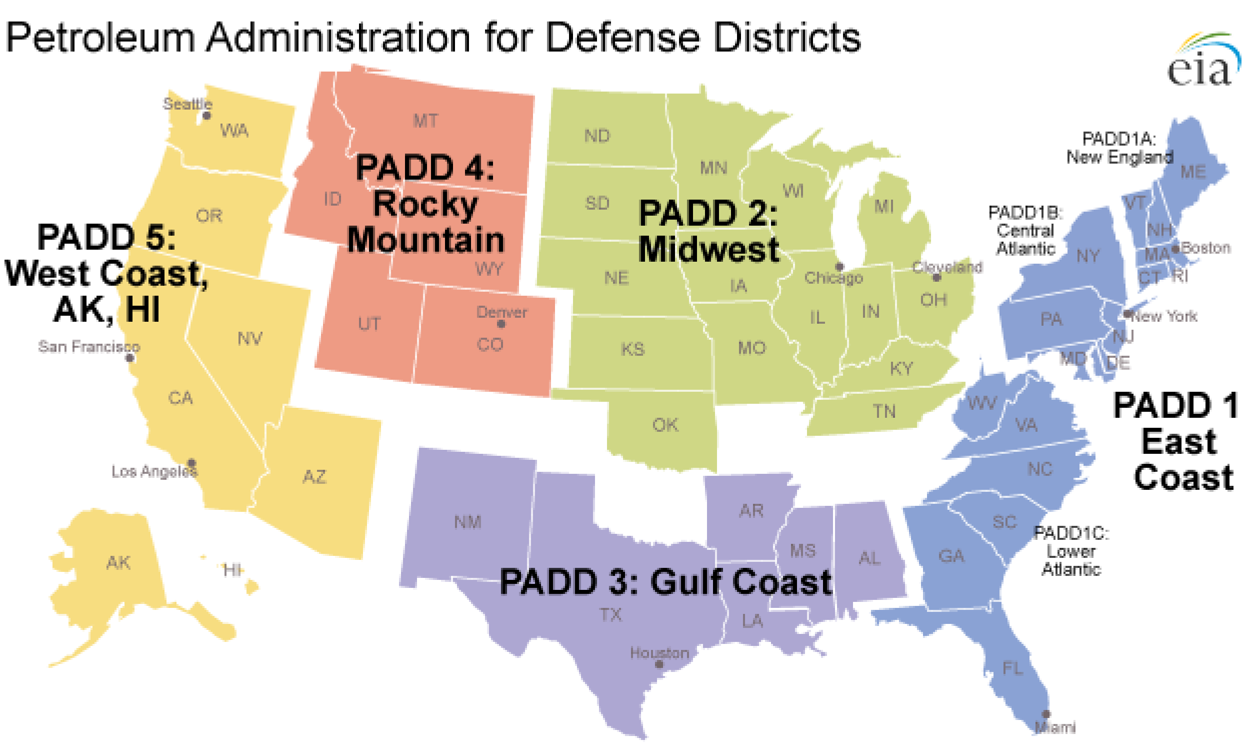


Figure 1 Petroleum Administration for Defense Districts (EIA 2014)

at the process-unit level. Using 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 supply types and ethanol production options (i.e., with corn and corn stover biomass feedstock), the WTW analysis of the energy use and GHG emissions showed that the overall WTW GHG emission changes associated with HOFVs were dominated by the positive impact associated with vehicle efficiency gains and ethanol blending levels. The refining operations to produce gasoline blendstock for oxygenate blending (BOB) for various HOF blend levels (E10, E25, and E40) had a much smaller impact on WTW GHG emissions.

However, the phase I study (Han et al. 2015) did not consider many of the operational and economic constraints and options that impact refinery operation, such as investing new process units to adapt to new HOF market demands, possible change in crude types, and possible increase in naphtha sales with increased ethanol blending level and HOF market share. Furthermore, the scope of Han et al. (2015) was limited to evaluating PADDs 2 and 3 operation changes with various HOF market share scenarios and ethanol blending levels. Finally, Han et al. (2015) used three typical configuration models of refineries in each PADD, which may not be representative of the aggregate response of all refineries in each PADD to various ethanol blending levels and HOF market scenarios.

In the three refinery configuration models (cracking, light coking, and heavy coking) used in Han et al. (2015), the share of HOF to total gasoline was assumed to be fixed. With high HOF scenarios included in the analysis, the cracking refinery configuration faced significant challenges to produce large shares of HOF with an E10 blending level. In practice, the ratio of HOF to regular gasoline will be different in different refineries to meet the market-aggregated HOF and regular gasoline demands. To examine the response by all refineries in major refinery regions, this HOF WTW phase II study employed regionally aggregated refinery models for the following six regions: PADDs 1, 2, 3, 4, and 5 (excluding CA) and CA separately.

In an aggregate refinery model, a single refinery model was developed to represent aggregation of the individual refineries in a specific region. Using aggregate refinery models, this phase II study examined the impacts of ethanol blending and HOF market shares on the refinery operations in these six regions. In addition, this phase II study conducted analyses using varied crude types and naphtha sales at various prices. Another assumption in Han et al. (2015) was no new refinery expansion in the existing refineries, which limited E10 HOF production volume by the cracking refinery configuration. To be able to satisfy large market demands of E10 HOF, the phase I study arbitrarily relaxed the RVP requirements by replacing the reformulated gasoline (RFG) RVP requirement of 7 psi in summer with the conventional gasoline (CG) RVP requirement of 9 psi in summer. This phase II study included refinery expansion to produce a pre-determined HOF volume. In particular, this study examined several refinery expansion options using refinery configuration models to investigate a practical refinery response to the increase in E10 HOF market demand.

The remainder of this report consists of six sections. Following this introductory section, Section 2 describes the key parameters for the HOF WTW analysis. Section 3 explains the petroleum refinery LP modeling methodology and analysis scope. Section 4 presents the key parameters for other WTW stages. Section 5 provides the results of the HOF scenarios using aggregate refinery models. Section 6 discusses the GHG emission and cost impacts of refinery expansion options using various configuration models. Finally, Section 7 presents the conclusions of this study.

2. Key Parameters for HOF WTW Analysis

The system boundary for the HOF WTW analysis consists of key stages for petroleum gasoline, corn ethanol, and corn stover ethanol pathways, as illustrated in Figure 2. While corn ethanol volume now dominates total U.S. ethanol production volume, corn stover ethanol is included to approximate the cellulosic ethanol group. The WTW system boundary of each pathway includes feedstock recovery (e.g., crude recovery, corn farming, or corn stover collection), feedstock transport, fuel production (e.g., petroleum refining or ethanol production), fuel transportation and distribution (T&D), and HOF combustion in vehicles.

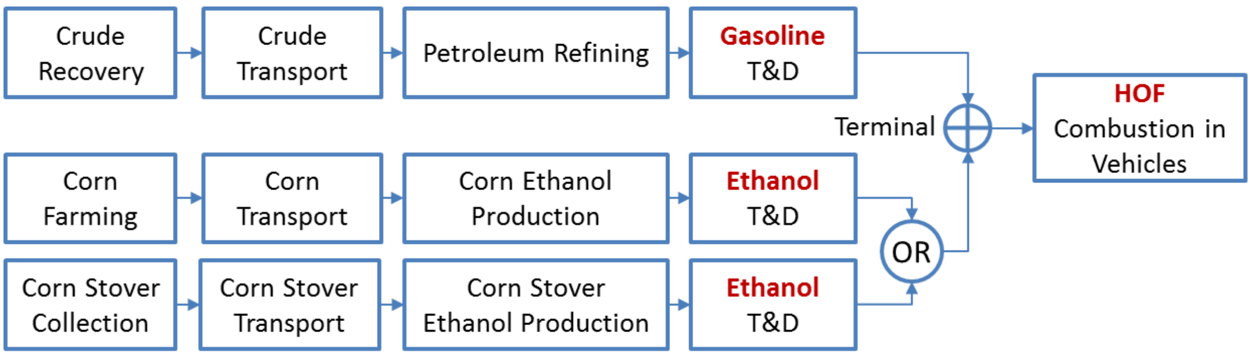


Figure 2 System boundary for the HOF WTW analysis

Two key stages for the HOF WTW analysis are petroleum refining and vehicle operation with HOF. While HOF production requires refinery operation changes that result in GHG emission intensity changes in petroleum refineries, HOFVs fueled by HOF can have increased efficiency Vehicle efficiency gains with HOF were assessed in phase I of this study, which is shown in Table 1 (Han et al. 2015; Theiss et al. 2016). Following the same logic as in the phase I study, this phase II study also considers a 5% miles per gasoline gallon equivalent (mpgge) fuel economy gain as the base case in this study for 100-RON HOF with E10, E25, and E40, while a 10% mpgge fuel economy gain is considered as a sensitivity case for E40. To present per-mile results that account for the impact of vehicle efficiency gains, this study uses 26.1 miles per gallon (mpg) for the fuel economy of the E10 regular vehicles, the average on-road fuel economy of a mid-size car. Thus, 5% and 10% vehicle efficiency gains result in 27.4 and 28.7 mpgge.

As described in Han et al. (2015), a petroleum LP model was used to address changes in refinery operations. The key parameters for refinery LP simulation are HOF specifications (especially with RON and RVP) and market shares. Continuing the HOF WTW analysis in Han et al. (2015), this study focuses on meeting 100 RON. This section discusses the details on HOF specification and HOF market shares.

Table 1 Summary of the engine and vehicle efficiency gains from various studies

Reference	RON	Efficiency gain (%)		Comment
		Engine	Vehicle	
Nakata et al. (2007)	100	7.4		Constant load, compression ratio = 13:1
Schwaderlapp et al. (2012)	98		5–7 with 12:1 compression ratio	Compared to 10:1 compression ratio with 95-RON gasoline
Speth et al. (2014)	98		2.2–3.2 without downsizing, 3.0–4.5 with downsizing	FTP-75 and HWFET[a] drive cycles; compared to a baseline naturally aspirated engine
Leone et al. (2015)	101		5.5–8.8	Compression ratio = 13:1; compared to 91-RON gasoline and a compression ratio of 10:1
Han et al. (2015)	100		5	10% for E40 as a sensitivity case

[a] FTP = Federal Test Procedure; HWFET = Highway Fuel Economy Test.

2.1. HOF Specifications

Finished gasoline is required to meet fuel standard specifications, including sulfur content, aromatic content, benzene content, distillation properties, vapor pressure (measured as RVP), octane rating, fuel DI, and others. In this study, octane number and RVP are the two most critical specification parameters to be met by HOF with different ethanol blending levels (Han et al. 2015).

2.1.1. Octane Number and Reid Vapor Pressure

The octane number of a fuel is a measure of its resistance to autoignition in a standard test engine. Engine efficiency can be improved by increasing compression ratio and/or by downsizing and downspeeding, but these approaches increase the propensity of knock and require the use of fuels with adequate octane number to prevent engine knock or counter uncontrolled auto-ignition of the end-gas. The higher the octane number of fuels, the higher chemical activation energies (higher temperature threshold) for self-ignition in engines under high compression.

Two standard measurement methods for the octane rating of a fuel component or blend are typically used (ASTM 2013a, 2013b; Kalghatgi 2001): the RON method (ASTM D2699) and the motor octane number (MON) method (ASTM D2700). The RON test method measures the knock intensity of a test fuel when the knock occurs by changing its compression ratio and comparing it with the knock intensity of a mixture of iso-octane (100 octane) and n-heptane (0 octane). The MON test method is similar to the RON test, but conducted at a higher engine speed (900 rpm) and with a higher engine intake air temperature (300°F) than those of the RON test (600 rpm and 125°F), using the same reference fuels (e.g., iso-octane and n-heptane). The MON test is intended to better represent aggressive operating conditions than the RON test is. The MON of test fuels is generally lower than the RON. In the United States, gasoline is currently labeled on the basis of the anti-knock index (AKI) or road octane, which equals (RON + MON)/2 or simply (R + M)/2. Currently, U.S. conventional regular gasoline is minimum 87 AKI (except in mountain states where it is minimum 85), representing approximately 92 RON and 82 MON. For modern engine designs RON is a better predictor of knock occurrence than MON or AKI.

RVP is a common measure of the volatility of gasoline, which is measured by the procedure defined in ASTM D5191 (ASTM 2015a)[1]. RVP is regulated by U.S. Environmental Protection Agency (EPA) to reduce evaporative emissions from gasoline that contribute to ground-level ozone. The EPA RVP regulations are only applicable in the summer season when evaporative emissions are significant and ozone air pollution is problematic. Also, in the United States, RVP requirements differ for CG and RFG, with the latter having more stringent RVP requirements. For example, the summer RVP standard for RFG is at approximately 7.0 psi for many U.S. ozone non-attainment areas. On the other hand, the summer RVP standard for CG is 7.8 psi or 9.0 psi, depending on the state (EPA 2015b). Also, the EPA provides a 1-psi waiver for E10 CG.

2.1.2. RON and RVP Specifications

Final gasoline product in a refinery generally consists of a large number of hydrocarbon components to achieve the target product specifications. 100-RON HOF can be produced via increased production of high-RON blending components, such as reformate, alkylate, and isomerate. The volumes and unique blending qualities of these components can be adjusted through flexibility in refinery operations. For example, a reformer can operate across a severity range from low to high. At higher severity, the reformer produces a smaller volume of reformates with a higher octane and RVP. However, such a smaller liquid volumetric yield from a reformer increases its production cost and energy intensity. Thus, trade-offs exist between RON, RVP, liquid yields, production costs, and energy intensities with different volumes of blending components from different refinery units and with different refining severities.

[1] In the EPA's Tier 3 Motor Vehicle Emission and Fuel Standards, EPA replaces the RVP measurement procedure (ASTM D323) with the dry vapor pressure equivalent (DVPE) measure procedure (ASTM D5191) because DVPE is more appropriate for ethanol-blended gasoline (EPA 2015a; ASTM 2015a, 2015b). DVPE is intended to be equivalent to RVP using a different test method.

Alternatively, 100-RON HOF can be produced by blending more ethanol than 10% by volume, since ethanol is a high-octane blending component (109 RON for neat ethanol). As in phase I, (Han et al. 2015), this study examined E10, E25, and E40 ethanol blend levels for HOF production, which are selected based on the following rationale:

- 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 a dispenser for ethanol blends higher than 25% by volume, due to Underwriters Laboratories' listing protocols for dispensers (Moriarty et al. 2014).
- The selection of E40 offers refiners the opportunity to use low-cost, low-RON BOB, such as 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.

Note that introduction of HOF with properties that are different from those of regular gasoline could incur additional infrastructure costs, which were investigated in a HOF market adoption study by the National Renewable Energy Laboratory (NREL) (Johnson et al. 2015).

Table 2 presents the octane and summer RVP specifications of regular gasoline, premium gasoline, and HOF (E10, E25, and E40). Note that the octane specifications of regular and premium gasoline are set to be consistent with the current specification of 87 and 93 AKI, respectively, while HOF's specification is defined by RON. In this study, the RFG summer RVP specification is set at 7 psi in all RFG regions, while CG summer RVP differs by region. For PADDs 3 and 4, the CG summer RVP for E10 (both regular and HOF) is set at 9 and 9.5 psi with a 1-psi waiver, respectively. On the other hand, the CG summer RVP for E10 (both regular and HOF) in all other regions (PADDs 1, 2, and 5 excluding CA and CA) is set at 10 psi with a 1-psi waiver. The 1-psi waiver is not applied to E25 and E40 HOF because a 1-psi waiver for gasoline above E10 would require legislation, which is uncertain. Note that Hirshfeld et al. (2014) showed that the impact of the 1-psi waiver on refinery GHG emissions was not significant at a higher ethanol blending level since RVP decreases with 20% or higher ethanol blending level as compared to E10, as shown in Figure 3 (API 2010; Andersen et al. 2010). Note that the LP model for each PADD assumed a constant RVP standard, while the RVP specification varies at the city, county, and/or state level. Although some refiners have opted out of the waiver, we applied the waiver throughout each PADD for simplicity. In this study, RFG shares in gasoline pools are set to 98, 15, 17, 0, 0, and 95% by volume in PADDs 1, 2, 3, 4, and 5 excluding CA and CA, respectively,

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

Specification	E10 regular	E10 premium	E10 HOF	E25 HOF	E40 HOF
Gasoline octane	87 AKI	93 AKI	100 RON	100 RON	100 RON
RFG summer RVP in all regions (psi)	7	7	7	7	7
CG summer RVP (psi)					
PADDs 1, 2, and 5 w/o CA and CA	10	10	10	9	9
PADD 3	9	9	9	8	8
PADD 4	9.5	9.5	9.5	8.5	8.5

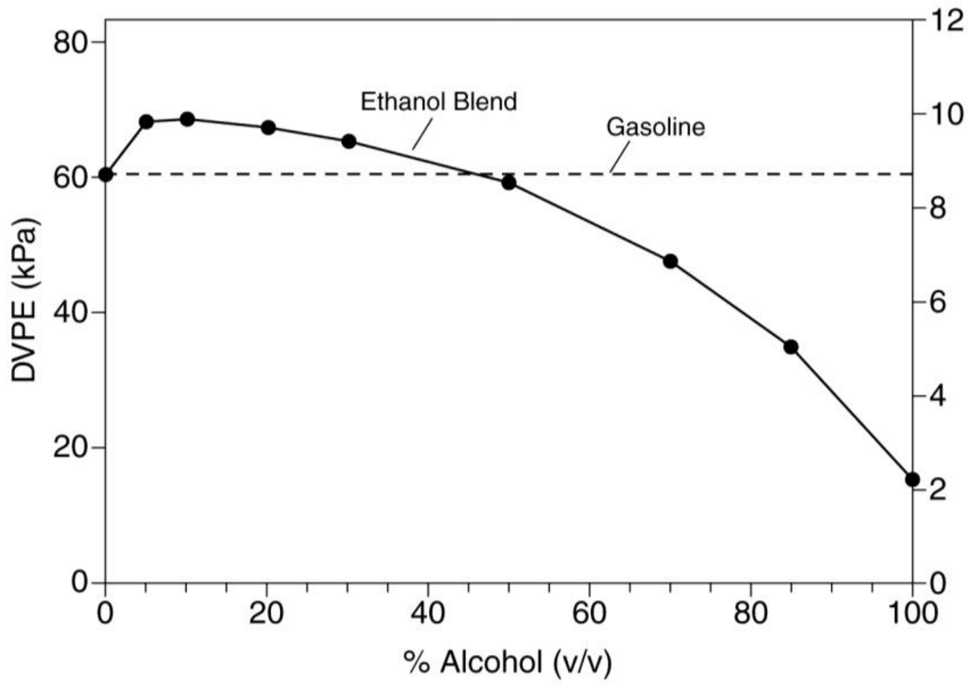


Figure 3 Impact of ethanol share in gasoline blends on the RVP (predicted dry vapor pressure equivalent) of the blend (Andersen et al. 2010)

while the remaining gasoline is CG. CG and RFG shares in aggregate U.S. gasoline pool are 70 and 30% by volume, respectively.

In practice, refiners produce a semi-finished gasoline product, namely BOB, that can be blended with ethanol to produce a finished gasoline at terminals. In this study, the refinery LP model estimates the blending properties (e.g., RON, RVP, AKI, etc.) of BOB for each labeled grade that is required to make the finished gasoline product at the specified ethanol content. Predicting the properties of a gasoline blend is complex, since the aggregate blending properties vary non-linearly with different shares of blending components. For example, ethanol has different blending properties based on the share of ethanol in the gasoline blend. The blending value of ethanol for RON increases from 118 with E10 to 121 with E25 and E40, as shown in Table 3. The change in the blending value of ethanol for RVP is more noticeable than that for RON, changing from 19.0 psi with E10 to 10.3 psi with E25 and to 9.0 psi with E40 in summer, and to 11.8 psi with E25 and E40 in winter. Detailed discussion on estimating blending values used in this study can be found in Han et al. (2015).

Table 3 Blending values of RON, AKI, and RVP for various gasoline blendstock components

Blending stream	Octane		RVP (psi)
	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
Isomerate	83–88	81–87	13–15
Naphtha	55–65	50–60	5–13
Natural gasoline	67–72	67–71	13–15
Ethanol to baseline gasoline (E10)	108–147	99–122	19.0
Ethanol to E10 HOF	118.0[a]	N/A	19.0
Ethanol to E25 HOF	121.0[a]	N/A	10.3/11.8[b]
Ethanol to E40 HOF	121.0[a]	N/A	9.0/11.8[b]

[a] Ethanol blending values to E10, E25, and E40 HOFs are calculated from Anderson et al. (2012).

[b] Summer/winter.

2.2. HOF market shares

The HOF market share is another key parameter affecting petroleum refinery operation, since the high shares of HOF could require high shares of high-RON blendstock, which could increase the energy and GHG intensities of petroleum refining for gasoline production. In the phase I analysis, we selected four HOF market penetration scenarios with three sets of HOF market shares (1, 3, 4, and 8—see Figure 4) out of eight scenarios that the NREL developed and analyzed by using the Automotive Deployment Options Projection Tool (ADOPT) (Johnson et al. 2015). Note that scenario 1 provides E25 HOF market shares only and scenario 8 provides E40 HOF market shares only, while scenarios 3 and 4 provide both E25 and E40 HOF market shares. Also, we selected the years 2022 and 2030 for refinery LP modeling of the four selected scenarios to examine the early and developed HOF market impacts. Since the ADOPT model did not estimate the fuel shares for the E10 HOF scenarios, the phase I study assumed that the fuel shares for the E10 HOF scenarios are consistent with those for the E25 HOF scenarios on an energy basis (i.e., calculating the volume of E10 by adjusting the volume of E25 with the ratio of lower heating value [LHV] of E25 to LHV of E10).

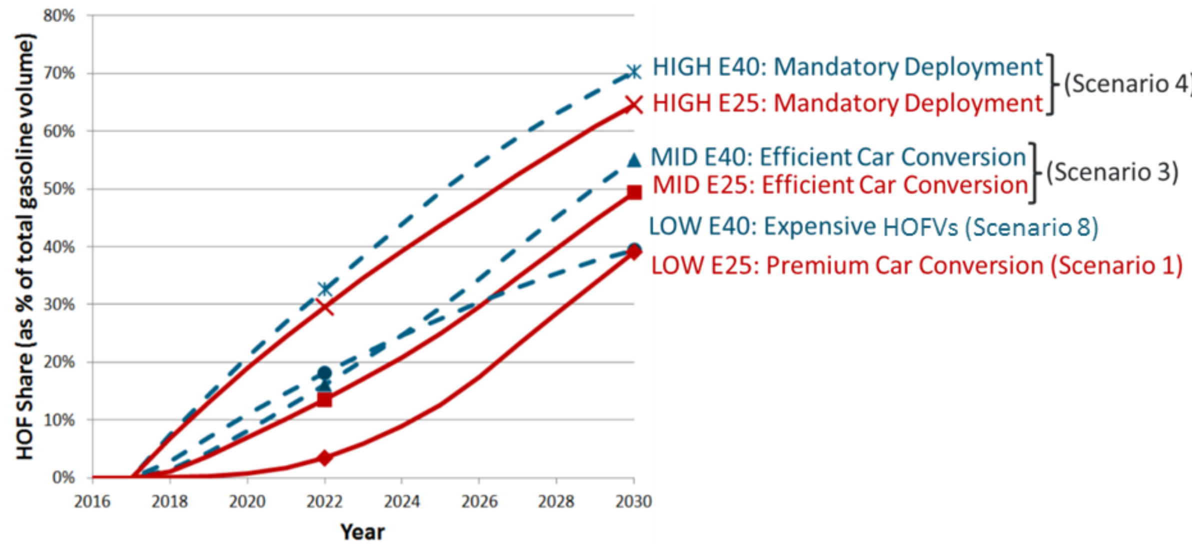


Figure 4 Selected HOF market penetration scenarios as predicted by NREL (Johnson et al. 2015)

Overall, the phase I study examined 18 HOF market scenarios (3 HOF market shares × 2 years × 3 ethanol blending levels) and a baseline scenario with 8% of E10 premium (93 AKI) and 92% of E10 regular (87 AKI) (representing the current market share of premium and regular gasoline). Detailed descriptions of the HOF market scenarios and the selection of the four scenarios and the target years can be found in Han et al. (2015).

Among the 18 HOF market scenarios, this phase II study focuses on 12 HOF market scenarios (4 HOF market scenarios x 3 ethanol blending levels) in addition to a baseline scenario with 8% of E10 premium (93 AKI) and 92% of E10 regular (87 AKI): scenario 3 for years 2022 and 2030 (MID in Figure 4), Scenario 1 and 8 for year 2022 (LOW in Figure 4), and scenario 4 for year 2030 (HIGH in Figure 4) for each ethanol blending level. The MID scenarios represent the average of HOF fuel shares from the ADOPT model for a given year, while the LOW scenario for 2022 and the HIGH scenario for 2030 were included to cover the range of the HOF fuel shares estimated by ADOPT. Table 4 presents the HOF market shares for the different market scenarios in 2022 and 2030.

Table 4 HOF market share scenarios for three ethanol blending levels in 2022 and 2030 as predicted by NREL (%) (Johnson et al. 2015)

HOF	Year	Scenario	E10 Non-HOF	E10 HOF	E25 HOF	E40 HOF
E10	2022	LOW	97	3	-	-
		MID	86	14	-	-
	2030	MID	51	49	-	-
		HIGH	35	65	-	-
E25	2022	LOW	97	-	3	-
		MID	86	-	14	-
	2030	MID	51	-	49	-
		HIGH	35	-	65	-
E40	2022	LOW	84	-	-	16
		MID	82	-	-	18
	2030	MID	45	-	-	55
		HIGH	30	-	-	70

3. Petroleum Refinery Modeling Methodology and Scope

3.1. Refinery Modeling Methodology

Two modeling methodologies are widely used to represent refinery industry operations: aggregate and configuration models. In an aggregate model, a single refinery model is developed to represent the aggregation of the individual refineries in a specific region. An aggregate model is commonly used in refinery analyses and can be calibrated to reported data for refineries in a region. However, an aggregate model might be over-simplified by assuming that all interactions among refineries in the aggregated region are conducted without loss, and it often lacks the granularity of analyzing impacts on a specific refinery configuration to produce various products. On the other hand, a configuration model is developed to represent a specific refinery configuration.

In the phase I analysis, we developed three generic configuration models in PADDs 2 and 3: cracking (with a fluidized catalytic cracking [FCC] unit but without a coker), light coking (with FCC and a coker processing light crude), and heavy coking (with FCC, a coker processing heavy crude, and a hydrocracker) refineries. With these configuration models, the phase I study examined responses by each configuration with each HOF scenario and showed the difficulty of producing E10 HOF by low-complexity refineries.

This phase II study focused on aggregated responses of refineries in major refinery segments by developing regionally aggregated refinery models for the following six regions: PADDs 1, 2, 3, 4, and 5 (excluding CA) and CA separately. The capacities of all the process operations for each region were volumetrically summed to create the aggregate refineries. For example, if the crude capacities of three refineries A, B, and C are 100, 150, and 200 thousand barrels per day (kBPD), the crude capacity for the aggregate model is 450 kBPD (A+B+C). For this study, 2014 refinery data as reported by the Energy Information Administration (EIA) was used as the basis for refinery operations and refined products production (EIA 2015a). This EIA data was separated into distinct PADD regions from which the modeling regions were defined. Estimates were used to sub-divide the aggregate PADD 5 in the EIA data into the sub-regions of CA and PADD 5 excluding CA. The aggregate models represent the reported feed and production for the aggregate refining centers.

Certain limitations exist with an aggregate model. While the aggregate model is the sum of individual refineries, the methodology does not model all of the individual refineries and then aggregate the modeling results. For example, PADD 3 comprises approximately 50 individual refineries with an aggregate capacity of almost 9 million barrels per day (MBPD) of crude inputs. An aggregate model of 50 refineries does not precisely reflect the wide range of operations from these 50 or so individual refineries.

3.2. Refinery Modeling Scope

Table 5 summarizes all refinery LP simulation scenarios. Using the aggregate models developed for the different regions, this study investigated three options:

1. The impact of ethanol blending levels (E10, E25, and E40) for HOF for three major regions (PADDs 2 and 3 and CA). To see the impact of ethanol blending level, all HOF scenarios (E10 regular gasoline and HOFs of E10, E25, and E40) for two given years (2022 and 2030) were simulated for three major regions (PADDs 2 and 3 and CA). The HOF market penetration scenarios were fixed to the middle scenario of HOF penetration (MID).
2. The impact of HOF market shares for the three regions. Two extreme scenarios for HOF scenarios with E10, E25, and E40 were selected: the minimum HOF scenario (LOW) in 2022 and the maximum HOF scenario (HIGH) in 2030.
3. The impact of E25 HOF for the other three regions (PADDs 1, 4, and 5 excluding CA). For these three regions, only E25 with the MID scenario was examined as a representative HOF scenario.

Table 5 Refinery LP simulation scenarios (HOF type, region, and market penetration)

	2022				2030			
Scenario	No HOF	E10	E25	E40	No HOF	E10	E25	E40
Base HOF scenarios with the aggregate model								
1. Impact of ethanol blending level	P2, P3, CA; MID	P2, P3, CA; MID	P2, P3, CA; MID	P2, P3, CA; MID	P2, P3, CA; MID	P2, P3, CA; MID	P2, P3, CA; MID	P2, P3, CA; MID
2. Impact of HOF market shares		P2, P3, CA; LOW	P2, P3, CA; LOW	P2, P3, CA; LOW		P2, P3, CA; HIGH	P2, P3, CA; HIGH	P2, P3, CA; HIGH
3. Other regions					P1, P4, P5 w/o CA; MID		P1, P4, P5 w/o CA; MID	
Sensitivity scenarios with the aggregate model								
1. Naphtha sale scenario							P2, P3; MID	
2. Crude type change scenario					P2, P3; MID		P2, P3; MID	
Additional scenarios with the configuration model								
Refinery expansion scenarios						USGC; MID		

Note that the first two baseline HOF scenarios focus only on the three major regions (PADDs 2 and 3 and CA), which account for approximately 85% of the U.S. refining capacity. In addition to these HOF scenarios, two sensitivity scenarios were examined:

1. The impacts of naphtha sale for other end uses. In the baseline HOF scenarios, gasoline excess to U.S. gasoline demand is sold as export while the refinery crude throughputs are maintained at full capacity. This sensitivity scenario evaluated the impacts of selling naphtha (low-valued blend components) from the refinery for other end uses, instead of exporting gasoline. This impact was examined for the two regions of interest (PADDs 2 and 3) and with the E25 in MID HOF market scenario in 2030.
2. The impacts of crude type changes. This sensitivity scenario consists of modeling the impact of crude slate focusing on scenarios for light tight oil (LTO) and heavy Canadian oil sands. The difference in American Petroleum Institute (API) gravity and sulfur content between these sensitivity scenarios is approximately 3 API points and 0.4 percentage points, respectively. Modeling of this sensitivity scenario was done in two regions of interest (PADDs 2 and 3) and with two scenarios (E10 without HOF and E25 MID HOF scenario in 2030).

The phase I study showed that large-scale production of E10 HOF was not practical without additional refinery expansion to meet HOF market demand. Thus, this phase II study examined several refinery expansion options to increase E10 HOF production with increased cost. Since the impact of investment options can vary by refinery configuration and complexity, this study was done by enhancing the previously developed configuration models in Han et al. (2015) by developing two U.S. Gulf Coast (USGC) medium-crude coking refineries with high- and low-octane configurations. While any refinery can have a different combination of operation units that impact the octane rating of gasoline, these high and low refinery configuration models were developed as being representative of “octane short” versus “octane long” refineries. Detailed discussion on these refinery configurations is provided in Section 6. Since summer gasoline is more challenging to produce compared to winter gasoline (due to the higher winter RVP allowance), these refinery expansion scenarios were examined for the summer period.

3.3. Development of Refinery LP Models

Table 6 summarizes the aggregate regions with respect to crude inputs and crude API gravity and conversion index in 2014 (EIA 2015b). Conversion index is defined as the conversion capacity (such as throughput to FCC, coker, and hydrocracker) divided by the crude capacity (refinery throughput). In general, higher conversion capacity is required to process heavier crude. Over 85% of the U.S. capacity is in PADDs 2 and 3 and CA, which is why some scenarios

Table 6 Crude inputs, crude API gravity, and refinery complexity index of the six study regions in 2014

Region	Crude Inputs		Crude API gravity	Conversion index
	BPD	%		
PADD 1	1,086,164	7	34.4	0.44
PADD 2	3,511,460	22	32.9	0.52
PADD 3	8,238,145	52	31.0	0.58
PADD 4	578,425	4	33.6	0.41
PADD 5	2,396,485	15	28.4	0.64
CA	1,715,672	11	25.4	0.79
PADD 5 w/o CA	680,813	4	36.1	0.34
U.S. Total	15,810,679	100	31.3	0.56

were performed on these specific regions. PADD 1, which accounts for about 8% of the U.S. crude capacity, processes a light crude slate and has a low conversion capacity. PADD 5 is composed of approximately 70% CA and 30% non-CA refineries, meaning that the heavy crude slate and high conversion index in PADD 5 are influenced primarily by CA.

The aggregate models were developed for two seasons (e.g., summer and winter), reflective of seasonal specification changes. The models produce fuels with the following specifications:

- All diesel is ultra-low-sulfur diesel 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 content is compliant with the EPA Mobile Source Air Toxics Rules (0.62% by volume).
- Fuel specifications (e.g., AKI, RON, and RVP) of gasoline grades are presented in Table 3.

To build baseline refinery LP models, this study:

1. Developed a calibration model for refineries in 2014 and
2. Used the 2014 calibration model to generate baseline models for future years (e.g., 2022 and 2030) using EIA forecasts for refinery input and production volumes (EIA 2015c).

These baseline models for future years were used as a basis for analyses to assess different impacts of various scenarios against these baseline models.

One of the key parameters in developing reliable baseline LP models is prices of crude, feeds, other fuels, and petroleum products. Table 7 presents three sets of prices for sample crudes and major refinery products for the study: annual U.S. average 2014 prices and forecasted prices for 2022 and 2030 as provided in the EIA's Annual Energy Outlook (AEO), using the reference case price sets (EIA 2015c). The material balance (purchases and sales) results of this study were not strongly influenced by these price sets because the production balances on regional inputs and outputs were held to these forecasted or assumed volume constraints. For example, if a future product demand is 100 kBPD, the model is set to produce 100 kBPD and this constraint is maintained regardless of prices.

Table 7 Price assumptions for refinery LP modeling

Product	Unit	2014	2022	2030
Brent	$/bbl	97.44	83.58	105.84
West Texas intermediate	$/bbl	91.98	77.28	99.54
Gasoline	$/gal	2.75	2.27	2.66
Diesel	$/gal	2.72	2.36	2.91
Jet	$/gal	2.59	2.20	2.80

Table 8 summarizes the crude inputs and product production from the 2014 calibration model and compares the product yields from the model with those from the 2014 EIA data. The comparison of the total U.S. product yields shows a very close alignment between the calibrated model and reported data for 2014.

The production, capacity, and configuration of the 2014 calibration model were used as a basis to generate new baseline refinery models for future years using EIA forecasts for refinery input and production. Growth rates (presented in Table 9) were applied to the 2014 basis to develop the refinery production targets for 2022 and 2030, which were based on the EIA's AEO forecast growth rates for U.S. demand (EIA 2015c). The models produced target volumes to meet U.S. demand and allowed for gasoline and diesel exports. The growth rates were applied uniformly for each region in the model.

Table 10 summarizes the crude inputs and product outputs from the 2022 and 2030 baseline models with the projected growth rates taken into account. The product yields (bbl/bbl crude) for the baseline models are compared with those from the EIA's reference case. The differences between the modeled and projected liquid product yields are not significant, except for diesel yields. The discrepancy in the diesel yields results from the differences in the export diesel projections by EIA and this study (Figure 5). While the EIA projection takes into account global market supply and demand in the future, the LP model in this analysis was designed to meet the U.S. gasoline and diesel demands while using exports as an outlet for the residual streams.

Table 8 Comparison of modeled results vs. EIA reported production data for 2014

Product	PADD 1	PADD 2	PADD 3	PADD 4	PADD 5	U.S. Total (Modeled)	U.S. Total (EIA 2015c)	
Crude inputs (BPD)	1,135,331	3,581,689	8,402,908	598,880	2,425,286	16,144,095	15,810,679	
Liq. petroleum gas (LPG)	45,839	96,367	341,888	13,587	81,780	579,461	641,860	
Finished gasoline	676,133	2,265,026	4,642,858	341,471	1,502,782	9,428,271	8,814,196	
Jet	98,137	242,634	836,733	38,022	431,926	1,647,453	1,632,904	
Diesel	350,515	1,081,074	2,834,783	196,402	592,839	5,055,613	4,888,241	
Residual fuel oil	126,909	214,000	452,978	50,232	175,444	1,019,563	1,019,529	
Product Yields (bbl/bbl crude)								Difference
LPG	0.04	0.03	0.04	0.02	0.03	0.04	0.04	0.00
Finished gasoline	0.60	0.63	0.55	0.57	0.62	0.58	0.56	0.03
Jet	0.09	0.07	0.10	0.06	0.18	0.10	0.10	0.00
Diesel	0.31	0.30	0.34	0.33	0.24	0.31	0.31	0.00
Residual fuel oil	0.11	0.06	0.05	0.08	0.07	0.06	0.06	0.00

Table 9 Annual growth rates of purchase and supply by petroleum refineries (%) (EIA 2015c)

Product	2014–2022	2022–2030
Purchase		
Crude	0.07	-0.24
Unfinished oil	-0.68	-0.72
Natural gas liquids	0.94	1.22
Supply		
LPG	1.77	0.27
Gasoline	-0.85	-1.55
Jet fuel	0.83	0.40
Diesel	1.34	0.47
Residual fuel oil	1.35	0.21
Other	2.25	0.83

Table 10 Comparison of modeled vs. EIA projected production for 2022 and 2030

Product	PADD 1	PADD 2	PADD 3	PADD 4	PADD 5	U.S. Total (Modeled)	U.S. Total (EIA 2015c)	
2022 crude inputs (BPD)	1,120,412	3,622,181	8,625,373	596,663	2,456,997	16,421,626	16,309,210	
LPG	36,192	104,966	409,546	13,259	72,809	636,771	619,402	
Gasoline	624,753	2,056,937	4,228,612	305,567	1,381,100	8,596,970	8,152,702	
Jet	106,189	263,437	884,730	38,707	446,651	1,739,713	1,757,084	
Diesel	393,903	1,279,391	3,330,228	225,639	747,925	5,977,087	5,072,845	
Residual fuel oil	124,308	217,483	408,252	51,076	172,891	974,010	1,051,676	
2022 product yields (bbl/bbl crude)								Difference
LPG	0.03	0.03	0.05	0.02	0.03	0.04	0.04	0.00
Gasoline	0.56	0.57	0.49	0.51	0.56	0.52	0.50	0.02
Jet	0.09	0.07	0.10	0.06	0.18	0.11	0.11	0.00
Diesel	0.35	0.35	0.39	0.38	0.30	0.36	0.31	0.05
Residual fuel oil	0.11	0.06	0.05	0.09	0.07	0.06	0.06	-0.01

Product	PADD 1	PADD 2	PADD 3	PADD 4	PADD 5	U.S. Total (Modeled)	U.S. Total (EIA 2015c)	
2030 crude inputs (BPD)	1,136,236	3,532,667	8,617,922	604,035	2,506,962	16,397,822	16,539,548	
LPG	23,368	102,390	432,047	13,316	68,531	639,653	628,150	
Gasoline	588,630	1,775,802	3,730,478	279,210	1,271,127	7,645,246	7,235,222	
Jet	117,714	289,445	1,023,237	41,763	505,653	1,977,812	1,940,762	
Diesel	453,549	1,432,355	3,574,617	259,330	823,294	6,543,145	5,170,426	
Residual fuel oil	121,920	213,526	409,910	48,818	166,442	960,616	1,066,529	
2030 product yields (bbl/bbl crude)								Difference
LPG	0.02	0.03	0.05	0.02	0.03	0.04	0.04	0.00
Gasoline	0.52	0.50	0.43	0.46	0.51	0.47	0.44	0.03
Jet	0.10	0.08	0.12	0.07	0.20	0.12	0.12	0.00
Diesel	0.40	0.41	0.41	0.43	0.33	0.40	0.31	0.09
Residual fuel oil	0.11	0.06	0.05	0.08	0.07	0.06	0.06	-0.01

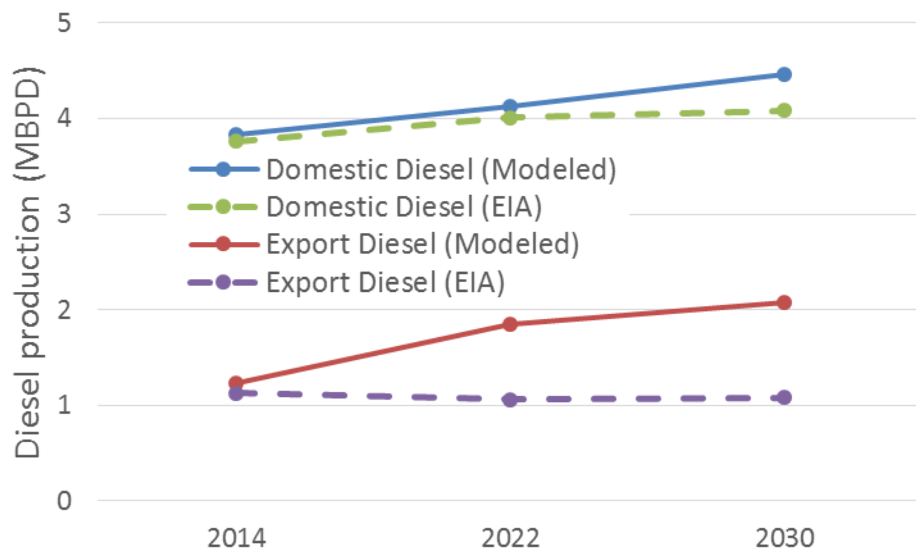


Figure 5 Diesel production by the refinery LP models and EIA

As a result, the modeled diesel production (both for domestic use and export) in this study increases gradually from the 2014 baseline by the growth rates presented in Table 9. On the other hand, the diesel export in EIA's AEO reference case is almost flat at the 2014 diesel export volume. Since the global gasoline and diesel demands (22.6 and 26.4 MBPD in 2012, respectively) would be significantly greater than the U.S. gasoline and diesel demands (8.7 and 3.7 MMPBD in 2012, respectively), this study assumes that the impact of the additional amount of export diesel on the global gasoline and diesel market would not be substantial (EIA 2015d).

The most notable change across the periods is the decrease in gasoline production and the increase in distillate (jet and diesel) production. For example, the gasoline to distillate (G:D) ratio was estimated to reduce from 1.4 in 2014 to 1.1 in 2022 and to 0.9 in 2030 in the modeled results. Similarly, EIA estimated a reduction from 1.4 in 2014 to 1.2 in 2022 and to 1.0 in 2030 (EIA 2015c). The G:D ratio reduction resulted in changes in conversion operations (e.g., less FCC, more hydrocracking, less alkylation, and less reforming) and higher hydrogen demands for diesel hydrocracking. The gasoline production reduction can be more significant in the E25 and E40 HOF scenarios, since a large amount of ethanol displaces petroleum gasoline blendstock. While the focus of this study is primarily on gasoline, the distillate balances become important for refinery operations with the decreasing demand for gasoline coupled with the growth of distillate.

4. Parameters for Other WTW Stages

In addition to crude refining and vehicle operations, the WTW system boundary for the HOF analysis includes other WTW stages, as shown in Figure 2, including crude recovery and ethanol production stages. These WTW stages and major parameters are discussed in this section.

4.1. Crude Recovery

The U.S. refining industry processes crude oils with different qualities from various sources, including Canada (oil sands and conventional crude), Mexico, the Middle East, Latin America, Africa, and other regions, as well as domestic production (shale oil and conventional crude). Table 11 presents the shares of crude oils to refineries in all five PADDs in 2014 and 2015 and to all U.S. refineries in 2020, which are based on EIA (2015b, 2015c, 2015d) and CAPP (2012). In addition,

Table 11 provides the shares of crude oil to refineries in all six regions estimated for this study (e.g., PADDs 1, 2, 3, 4, and 5 without CA and CA separately) from EIA (2015b, 2015c, 2015d) and additional 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, shale oil, and heavy crude (such as oil sands). The oil sands share in the crude mix is a key WTW analysis parameter because of the difference in GHG emission intensities of conventional crude recovery and oil sands recovery/upgrading (Cai et al. 2015). The EIA (2015b, 2015c, 2015d) and CAPP (2012) project that the oil sands share in the crude mix to U.S. refineries will stay almost flat until 2020 (11% in 2015 to 12% in 2020). In 2015, the oil sands share is highest in PADD 2 at 32%, followed by PADD 4 at 26%, due to the available transportation logistics of oil sands to PADDs 2 and 4. In our projection, oil sands are still a dominating crude feedstock for PADDs 2 and 4. Note that EIA (2015c) projects that the shale oil share in the crude mix to U.S. refineries will grow from 17% of total crude inputs in 2015 to 22% in 2020.

Cai et al. (2015) examined the oil sands pathways in detail by using the energy intensity provided by Englander et al. (2015) for different oil sands recovery operations (i.e., surface mining and in-situ production) and various crude products from these operations (i.e., upgraded synthetic crude oil and diluted bitumen). 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 oil sands recovery, as provided in Yeh et al. (2014).

Table 11 Reported shares of crude oils to refineries in U.S. in 2014 and 2020, with modeled shares of crude oils for future years (%)

Region	Target year	U.S. conv. crude	U.S. shale oil	Canada oil sands	Canada conv.	Mexico	Middle East	Latin America	Africa	Other
PADD 1	2014[a]	31	9	14	12	3	9	3	16	3
	Future[b]	0	29	5	2	0	21	0	43	0
PADD 2	2014[a]	34	10	31	25	0	1	0	0	0
	Future[b]	24	24	31	22	0	0	0	0	0
PADD 3	2014[a]	46	14	1	1	9	15	14	1	0
	Future[b]	45	11	0	0	9	26	9	0	0
PADD 4	2014[a]	44	13	24	19	0	0	0	0	0
	Future[b]	0	49	32	19	0	0	0	0	0
PADD 5	2014[a]	42	12	5	4	1	21	11	2	2
	Future[b]	43	11	1	4	0	29	12	0	0
PADD 5 w/o CA	Future[b]	19	39	4	14	0	23	0	0	0
CA	Future[b]	53	0	0	0	0	31	17	0	0
U.S.	2014[a]	41	12	10	8	5	12	9	2	1
	2020[a]	44	22	12	7	3	6	5	1	0

[a] Based on EIA (2015b, 2015c, 2015d) and CAPP (2012).

[b] Estimated for this study from the projections by EIA (2015b, 2015d), with additional inputs from the DOE Office of Energy Policy and Systems Analysis.

Table 12 GHG emissions (g CO_2e/MJ of fuel products) from various oil sands recovery and production operations (Cai et al. 2015)

Process	Conv. crude	Mining + SCO[a]	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

[a] Synthetic crude oil.

Table 13 presents the key parameters affecting GHG intensities in the crude recovery stage of conventional crude and shale oil. The GHG intensities of conventional crude oil recovery in this study are based on default parameters in the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET®) Model for conventional crude recovery (Burnham et al. 2011), while the parameters for shale oil recovery are based on the energy intensity and GHG emissions provided by Brandt et al. (2015) and Ghandi et al. (2015) for Bakken and Eagle Ford plays, respectively. While shale oil recovery is slightly more energy efficient than conventional crude recovery, the gas flaring intensity of the shale oil recovery is much higher than that of conventional crude recovery (especially in the Bakken play), which results in higher GHG emission intensities in the crude recovery stage for shale oil compared to conventional crude.

Table 13 Key parameters for crude recovery of conventional crude and shale oil

Parameter (unit)	Conventional crude	Shale oil (Bakken)	Shale oil (Eagle Ford)
Crude recovery energy efficiency (%)	98.0	98.8	98.5
CO_2 emissions from associated gas flaring (g/MJ)	0.03	5.36	1.36
CH_4 emissions from associated gas venting (g/MJ)	0.039	0.062	0.061

4.2. Ethanol Production

According to the Renewable Fuels Association, U.S. fuel ethanol production in 2015 was estimated at 14.7 billion gal, largely produced from corn (Renewable Fuels Association 2016). Corn ethanol is currently being used as a blending component to produce regular and premium gasoline (E10). However, cellulosic feedstocks—including 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—could play an important role for future bioethanol production. Oak Ridge National Laboratory (ORNL 2011) estimated that 243–767 million dry tons of biomass could be available in 2030. If all of the biomass resource were to be used for ethanol production, with a yield of 80 gal of ethanol per dry ton of biomass the total ethanol production could reach 19–61 billion gal/yr.

As shown in Figure 2, this study examines the corn ethanol and the corn stover ethanol as ethanol blendstock to produce 100-RON HOF. The corn stover ethanol is assumed as a surrogate for cellulosic ethanol. Argonne has been expanding and updating the GREET model to evaluate the lifecycle GHG emissions associated with transportation fuels and vehicle technologies on a continuing basis, including bioethanol production pathways from various sources, such as corn, sorghum, corn stover, forest residue, switchgrass, miscanthus, willow, and poplar (Argonne National Laboratory 2015). The system boundaries and activities covered in the lifecycle analysis of corn ethanol are shown in Figure 6. Table 14 summarizes key WTW parameters for corn and corn stover ethanol pathways, which are based mainly on the analysis by Wang et al. (2012) and subsequent updates on the fertilizer applications from the latest survey of corn farming by the U.S. Department of Agriculture (USDA 2014), corn ethanol production process updates by Mueller and Kwik (2013), and the implementation corn oil extraction in dry milling corn ethanol plants examined by Wang et al. (2015). Recently, Canter et al. (2015) examined and compared the GHG emissions from integrated corn and corn stover ethanol production with those from standalone ethanol facilities with either corn grains or corn stover. Qin et al. (2016, 2015) documented detailed modeling of land use changes and associated GHG emissions of ethanol pathways, including tillage (i.e., conventional, reduced, and no tillage), corn stover removal (i.e., at 0, 30, and 60% removal rate), and organic matter input techniques (i.e., cover crop and manure application).

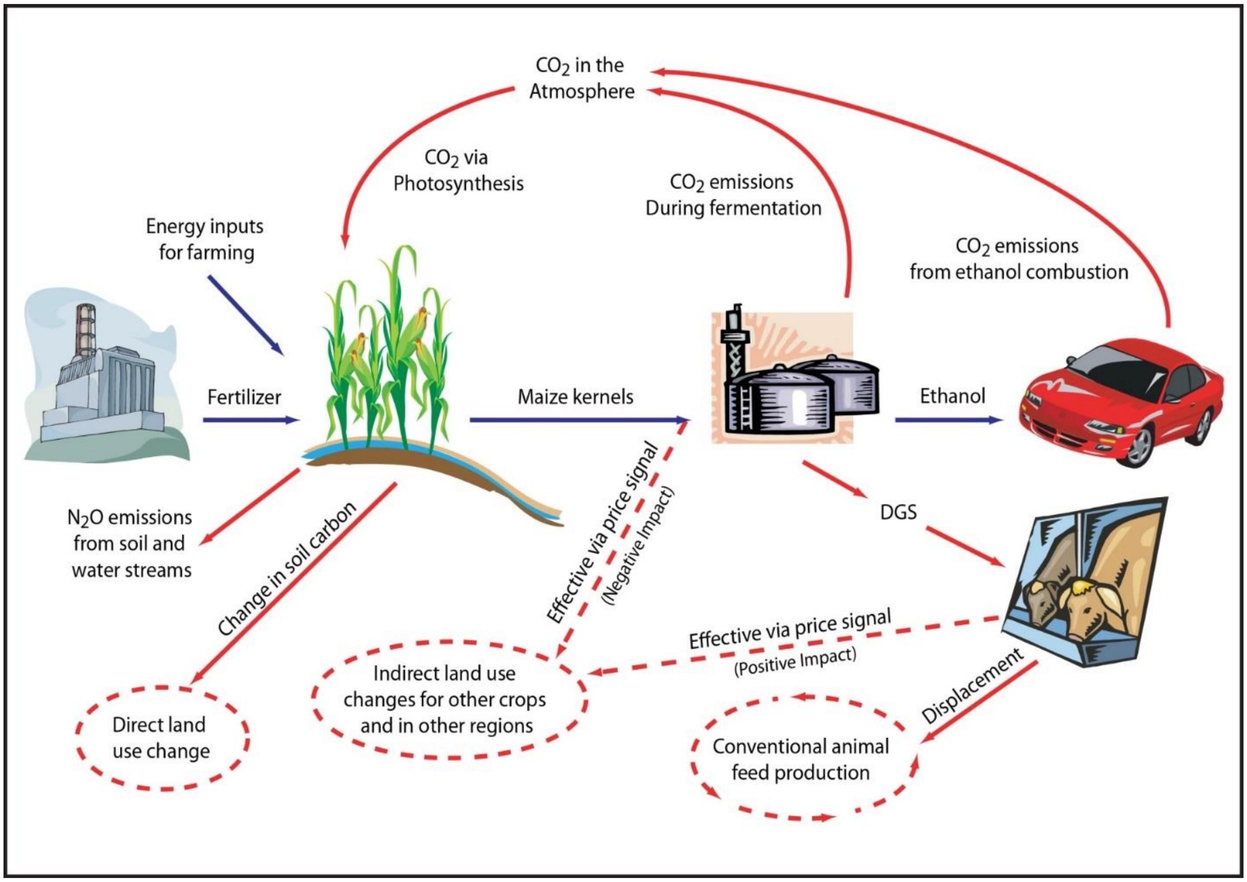


Figure 6 System boundaries for corn ethanol lifecycle analysis

Table 14 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_2O conversion rate of N fertilizer (%)	1.525[a]			
Corn/corn stover ethanol production				
Parameter (unit)[c]	Dry mill without corn oil extraction	Dry mill with corn oil extraction	Wet mill	Corn stover
Ethanol yield (L/dry tonne of corn or corn stover)	510[b]	514[b]	476[b]	376[a]
Ethanol plant fossil energy use (MJ/L of ethanol)	7.49[a]	7.36[b]	13.2[a]	
DGS yield (dry kg/L of ethanol)	0.675[a]	0.646[b]		
CGM yield (dry kg/L of ethanol)			0.147[a]	
CGF yield (dry kg/L of ethanol)			0.632[a]	
Corn oil yield (dry kg/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 (%)	18[b]	73[b]	9[b]	

[a] Based on Wang et al. (2012).

[b] Based on Canter et al. (2015).

[c] DGS = distillers grains with solubles; CGM = corn gluten meal; CGF = corn gluten feed.

5. Results for HOF Scenarios Using Aggregate Refinery LP Models

5.1. Refinery LP Modeling Results

The base HOF scenarios were simulated with the aggregate refinery LP models to examine the impacts on regional refineries of ethanol blending levels (E10, E25, and E40), HOF market shares, and PADD regions. The aggregate model in this study has more operational flexibility than the configuration models used in the phase I study. Using configuration models, the previous study by Han et al. (2015) identified significant challenges in increasing production of E10 HOF with current refinery configurations. However, even with the flexibility of the aggregate model, the scale of E10 HOF production remained limited. That is, half of the E10 HOF market penetration scenarios were infeasible, meaning that the aggregate models could not satisfy all the refinery operational constraints to produce the specified E10 HOF market shares. The other market scenarios, while feasible, had excessively high marginal costs for meeting octane targets in the solution set. A high-octane marginal cost indicates the octane specification is expensive to achieve. The infeasible scenarios were typically associated with summer gasoline production for the high-market shares of E10 HOF.

There are refinery operation options that could be deployed to potentially generate feasible solutions, such as relaxing production constraints, lowering HOF market shares, or adding capacity to specific units. The phase I study relaxed a key production constraint: zeroing out RFG shares for the E10 scenarios and consequently removing the 7-psi RVP constraint for RFG. To address the infeasible scenarios, this phase II study applied an outside battery limits (OSBLs) improvement, a refinery expansion option that includes storage, blending, and piping systems. In this context, we also included the splitters and fractionators to separate streams. The OSBL improvement allowed more selective and flexible blending strategies, which can increase production of high-octane blending components for HOF. This OSBL improvement was applied for all of the E10 scenarios for consistent modeling.

5.1.1. Impacts of Ethanol Blending Levels and HOF Market Shares in PADDs 2 and 3 and CA

To examine the impacts of ethanol blending levels and HOF market shares, the LP simulations were conducted in three major petroleum refining regions: PADDs 2 and 3 and CA.

For HOF production, key constraints are RON and RVP. To meet the RON requirement, refineries need to produce more high-octane components internally, if with a lower ethanol blending level. Figure 7 presents the total gasoline pool of the non-HOF (baseline) scenario and the E10, E25, and E40 HOF scenarios with the 2030 HIGH HOF market shares. In the figure, the stacked bars are arranged by the order of their RON values: the highest RON component (i.e., reformate) is at the bottom, while the lowest RON component (i.e., naphtha) is at the top

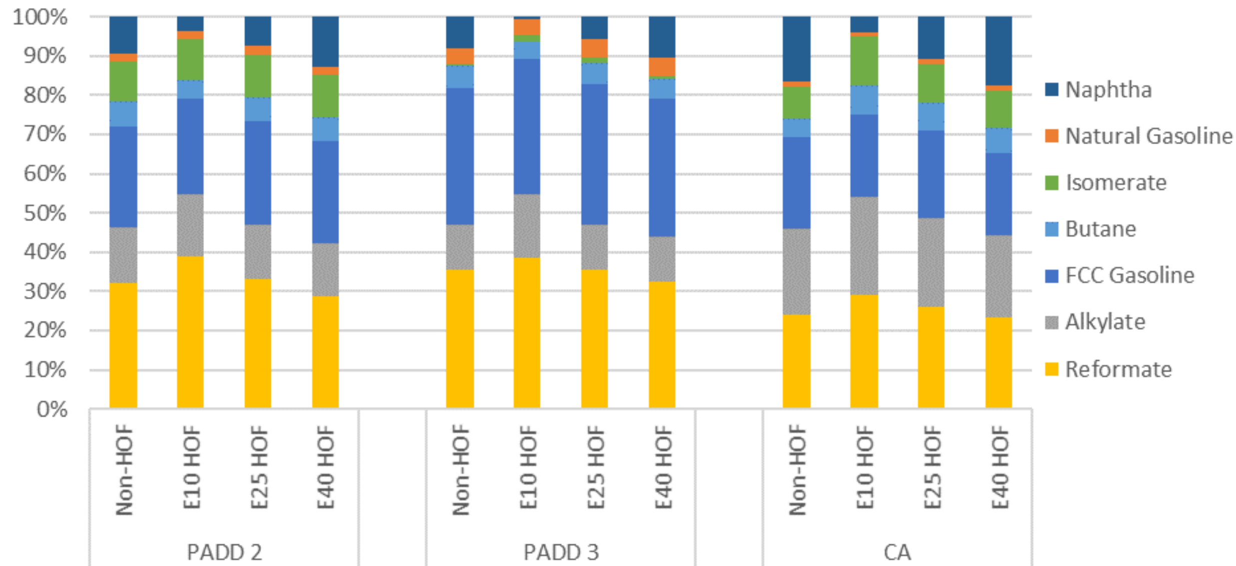
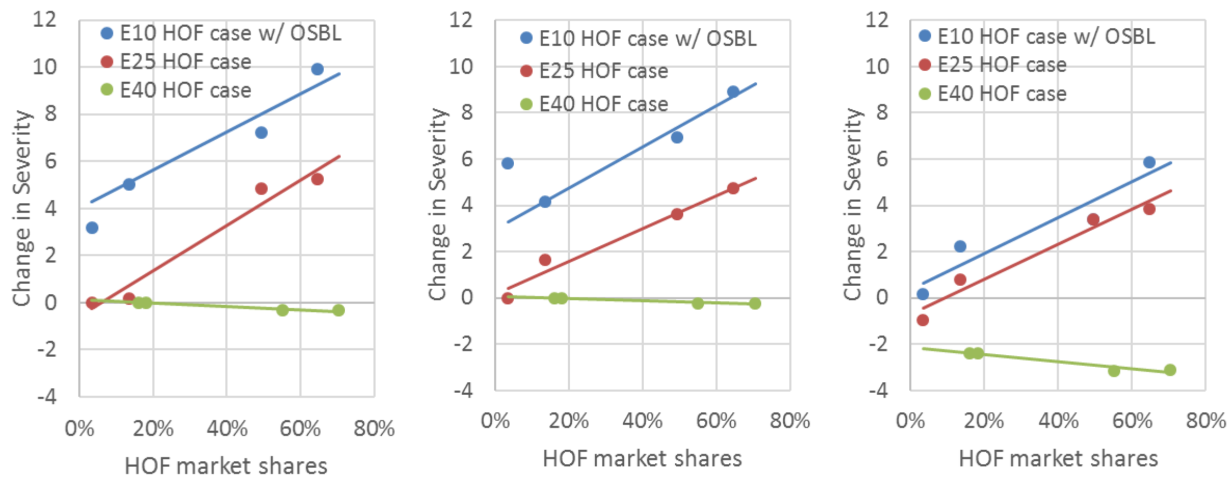


Figure 7 Total gasoline BOB pool of the non-HOF (baseline) scenario and the E10, E25, and E40 HOF scenarios with the 2030 HIGH HOF market shares

of the stack. As shown in the figure, the share of reformate and alkylate for the HOF scenarios increases as the ethanol blending level decreases from E40 to E25 and E10. In addition to high octane, the RVP values for reformate (3–5 psi) and alkylate (4–6 psi) are relatively low, which helps refineries to meet the RVP standards for HOF. On the other hand, the share of naphtha (with low octane ratings) decreases noticeably as the ethanol blending level decreases from E40 to E25 and E10. A higher share of naphtha in gasoline pools makes them relatively inexpensive–and often desirable—because naphtha requires little refinery processing. This indicates that the E40 scenarios have the least difficulty meeting gasoline specifications, that is, RON and RVP. Meanwhile, the share of FCC gasoline, with a medium RVP and medium RON, remains unchanged. Note that the reformate shares in CA are much lower than those in the other regions due to the limitation of aromatics content in gasoline in CA.

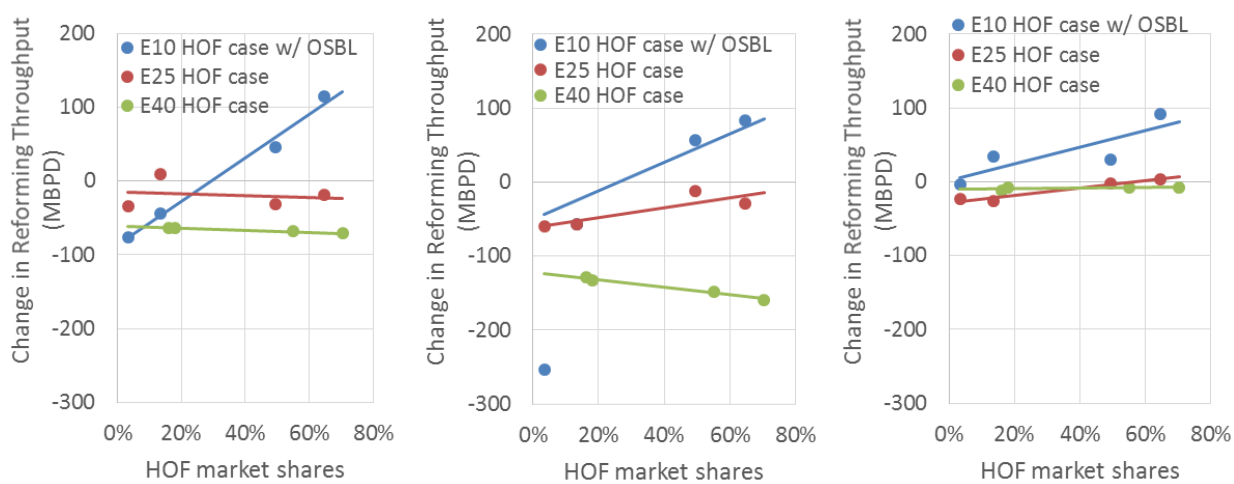
Among various operational changes in refineries to produce the pre-defined HOF, one key process operation used to control refinery octane production is the reformer. The refinery can adjust the reformer two ways for octane control. First, the severity of the reformer operation can be adjusted, whereby a high severity translates to high octane. The downside of increasing severity is a reduction in the liquid yield, which impacts refinery economics. Note that the severity also depends on the type of reforming unit. Continuous catalytic reformers (CCRs) can achieve higher RON (100–101) than semi-regenerative catalytic reformers (SRRs, 97–98). Second, the feed or throughput to the reformer can change. Reformer feed is naphtha, and naphtha could bypass the reformer and blend directly into gasoline. Because both the severity and the throughput of the reformer can influence the octane production, a commonly used metric is severity times reforming throughput in BPD (Sev. x BPD). When refinery Sev. x BPD increases, this often indicates the need to increase refinery octane production.

Figures 8 and 9 show the changes in severity and reforming throughputs for the E10, E25, and E40 scenarios relative to the non-HOF scenarios in PADDs 2 and 3 and CA. Note that the E10 HOF scenario includes the OSBL improvement. Even with the OSBL improvement, the E10 HOF



(a) PADD2 (b) PADD3 (c) CA

Figure 8 Change in reforming severity (RON point change) for the E10, E25, and E40 HOF scenarios relative to the non-HOF baseline scenario in (a) PADD 2, (b) PADD 3, and (c) CA



(a) PADD2 (b) PADD3 (c) CA

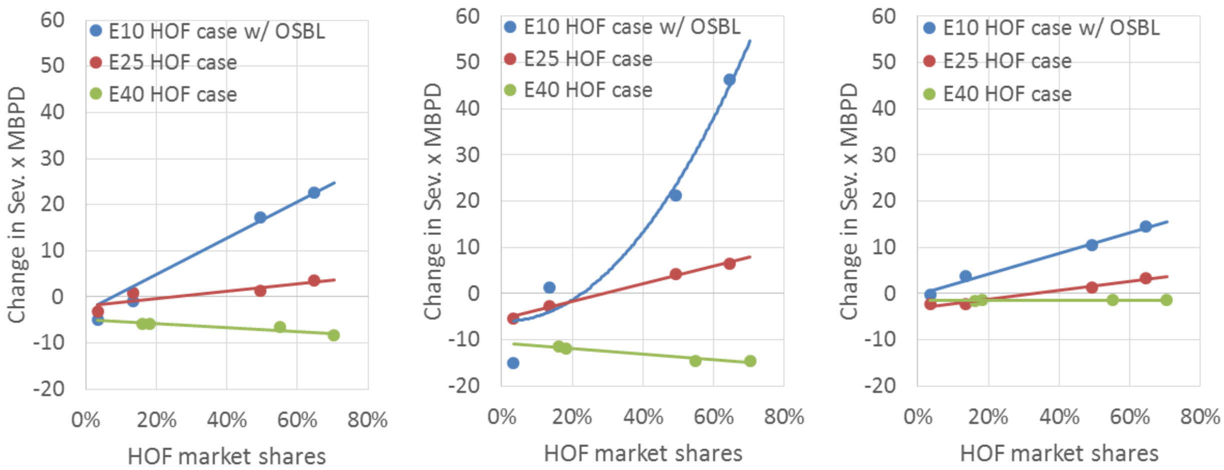
Figure 9 Change in reforming throughput of the E10, E25, and E40 HOF scenarios relative to the non-HOF baseline scenario in (a) PADD 2, (b) PADD 3, and (c) CA

scenarios show significant increases in the reforming severity (10, 9, and 6 RON points in PADDs 2 and 3 and CA, respectively) and throughputs to meet the 100-RON specification as the HOF market shares increase.

Note that the changes in reforming throughput of the E10 HOF scenario relative to the baseline non-HOF scenario are negative at low HOF market shares (e.g., 3% in PADD 2, 14% in PADD 3, and 3% in CA), which is caused by the OSBL improvement only applied to E10 HOF scenarios. The OSBL improvement enables better blending, including separation of light and heavy reformates for the CG and HOF BOB pools, respectively. Thus, the E10 HOF scenarios with the OSBL improvement requires less volume of reformates at low HOF market shares compared to the non-HOF baseline scenario without the OSBL improvement.

In the E25 HOF scenarios, the reforming severity with a low HOF market share (3%) is almost the same as the severity of the non-HOF scenario but increases linearly with HOF market shares. On the other hand, the severity in the E40 HOF scenarios are almost identical with that in the baseline non-HOF scenarios in PADDs 2 and 3, while the severity in the E40 HOF scenarios in CA are even lower than that in the baseline non-HOF scenarios. The change in reforming throughputs of the E25 and E40 HOF scenarios are nearly constant throughout the range of HOF market shares. Thus, the impact of HOF production on the reforming throughputs are not significant with E25 and E40. Note that the changes in reforming throughputs for the E25 and E40 HOF scenarios are generally negative, meaning that these HOF scenarios require a smaller volume of reformates. This is expected, since the gasoline BOB is reduced by the higher ethanol blending volume.

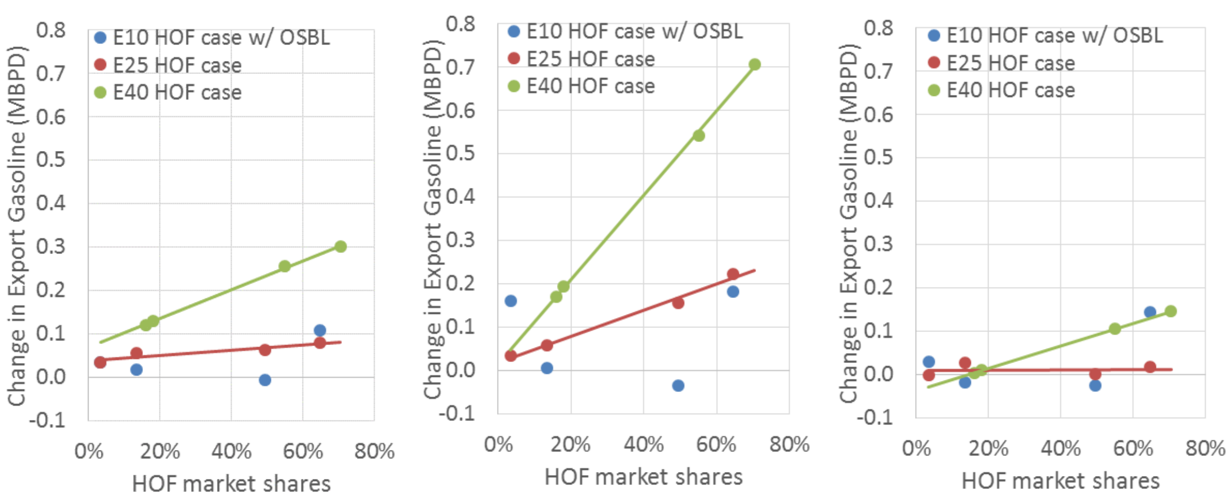
Figure 10 shows the change in Sev. x BPD for the E10, E25, and E40 scenarios relative to the non-HOF scenarios. The E40 scenarios have a reduction in Sev. x BPD as the HOF market share increases, while the Sev. x BPD increases in the E10 and E25 scenarios with an increasing HOF market share. Especially, the Sev. x BPD of the E10 HOF scenarios depends highly on the HOF market shares. In other words, as the HOF market share increases, refineries producing E10 HOF simply run out of octane. These results are consistent with the phase I findings. With a higher ethanol blending level, refineries have less pressure to produce octane because of the higher ethanol addition. Moreover, a higher ethanol blending level also helps refineries to meet the RVP requirements, since the blended RVP of ethanol decreases with a higher ethanol blending level.



(a) PADD2 (b) PADD3 (c) CA

Figure 10 Change in severity x BPD of the E10, E25, and E40 HOF scenarios relative to the non-HOF baseline scenario in (a) PADD 2, (b) PADD 3, and (c) CA

In this phase II study, the volumes of crude inputs to refineries and U.S. gasoline, jet, and diesel demands are fixed for all scenarios in a given year. To maintain the material balances, coupled with higher volumes of ethanol, there will be pressure to increase gasoline exports, as shown in Figure 11. In the E25 and E40 HOF scenarios, the amount of export gasoline increases almost linearly with HOF market share in PADDs 2 and 3, which are roughly equal to the incremental amount of ethanol used to produce HOF, while the export gasoline in CA increases linearly with HOF market share for the E40 HOF scenarios and remains flat for the E25 HOF scenarios. The E10 HOF scenario shows no general trends in export gasoline throughout the scenarios.



(a) PADD2 (b) PADD3 (c) CA

Figure 11 Changes in export gasoline relative to the non-HOF baseline scenario in (a) PADD 2, (b) PADD 3, and (c) CA

5.1.2. Impacts of E25 HOF on Refineries in Different Regions

The impacts of HOF production can be different by region due to the differences in the conversion process capacities by region. Figure 12 presents the total gasoline pool of the non-HOF (baseline) and the E25 HOF scenarios with the 2030 MID HOF market shares for all six regions. The total gasoline pools are nearly identical between the baseline non-HOF scenarios and the E25 HOF scenarios in the same region, which shows that the impacts of E25 HOF production on the gasoline pools are minimal throughout the regions.

Table 15 provides the reforming severity, throughput, and Sev. x BPD of the baseline non-HOF and E25 HOF scenarios with the 2030 MID HOF market shares for all six regions. Throughout the regions, the reforming severities in the E25 HOF scenarios increase by 3.7–5 points relative to the baseline non-HOF scenarios. On the other hand, the changes in reforming throughputs are not significant, ranging from -4.3% in PADD 4–1.8% in CA. Therefore, the changes in Sev. x BPD are generally small except for CA. In other words, CA refineries could have more difficulty to meet the 100-RON requirement for E25 HOF than refineries in the other regions do because of the limitation of allowable reformate blending.

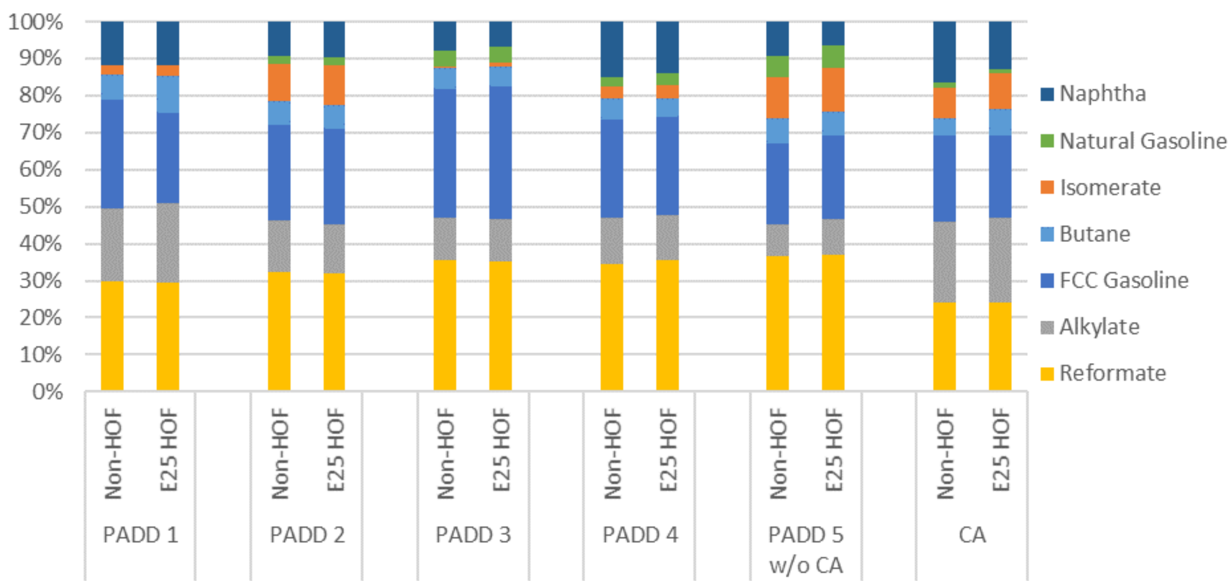


Figure 12 Total gasoline pool of the E10 non-HOF (baseline) and the E25 HOF scenarios with the 2030 MID HOF market shares for all regions

Table 15 Severity, throughput, and Sev. x BPD of the non-HOF (baseline) and the E25 HOF scenarios with the 2030 MID HOF market shares for all six regions

Product	PADD 1	PADD 2	PADD 3	PADD 4	PADD 5 w/o CA	CA
Reforming severity						
Non-HOF	92.6	90.3	90.2	94.6	92.3	93.5
E25 HOF	97.6	95.6	95.0	98.6	96.0	97.4
Change	5.3%	5.8%	5.2%	4.2%	4.0%	4.1%
Total reforming throughput (MBPD)						
Non-HOF	0.19	0.59	1.45	0.10	0.14	0.22
E25 HOF	0.18	0.57	1.42	0.10	0.13	0.23
Change	-3.7%	-3.2%	-2.0%	-4.3%	-0.5%	1.8%
Sev. x MBPD						
Non-HOF	18	53	130	10	12	21
E25 HOF	18	54	135	10	13	22
Change	1.5%	2.4%	3.1%	-0.3%	3.5%	6.0%

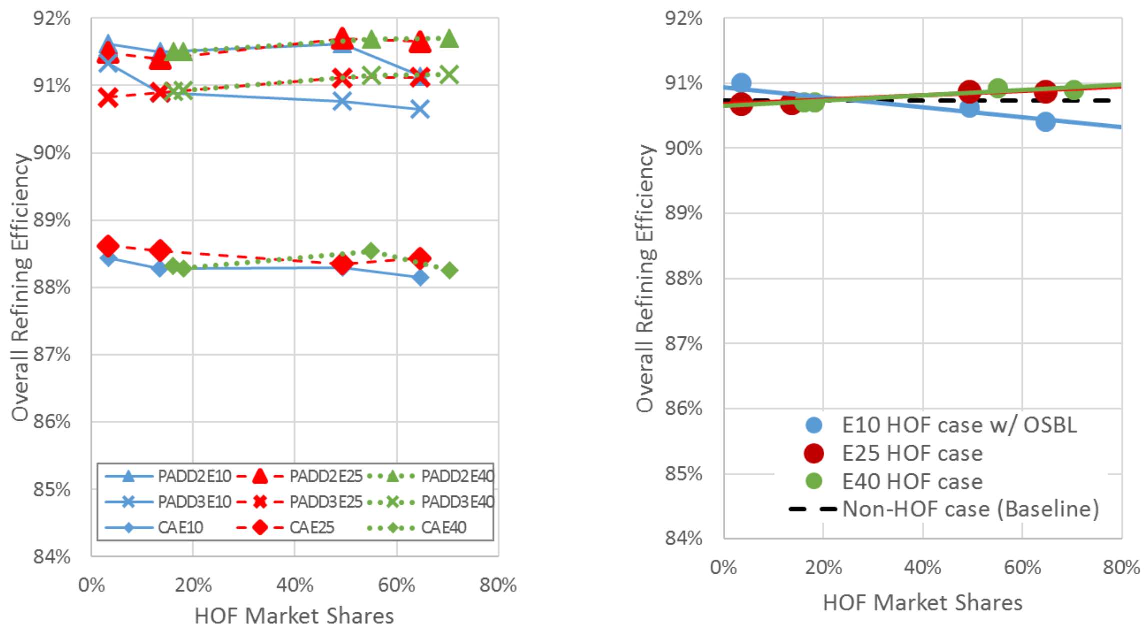
5.2. Energy Efficiencies and WTW GHG Emissions of Gasoline by Lifecycle Stage under Different HOF Scenarios

The refinery LP model generated volumetric and mass flow rates of refinery inputs, outputs, and all intermediate streams as well as utility consumption rates (e.g., electricity, steam, process fuels, water, and catalysts). Using these refinery LP model results, energy efficiencies of overall refinery and specific refinery products were calculated using the process-level allocation method elaborated in Elgowainy et al. (2014) and Han et al. (2015).

5.2.1. Impacts of Ethanol Blending Levels and HOF Market Shares on Energy Efficiencies and GHG Emissions in PADDs 2 and 3 and CA

Figure 13 presents the overall refining energy efficiency of the E10, E25, and E40 HOF scenarios versus HOF market shares in PADDs 2 and 3 and CA as well as for the aggregated overall refining efficiency of these regions, or the weighted average of the refining efficiency of the major refining regions (e.g., PADDs 2 and 3 and CA) by their production volumes. The dashed line is the refining efficiency of the baseline non-HOF scenario for comparison.

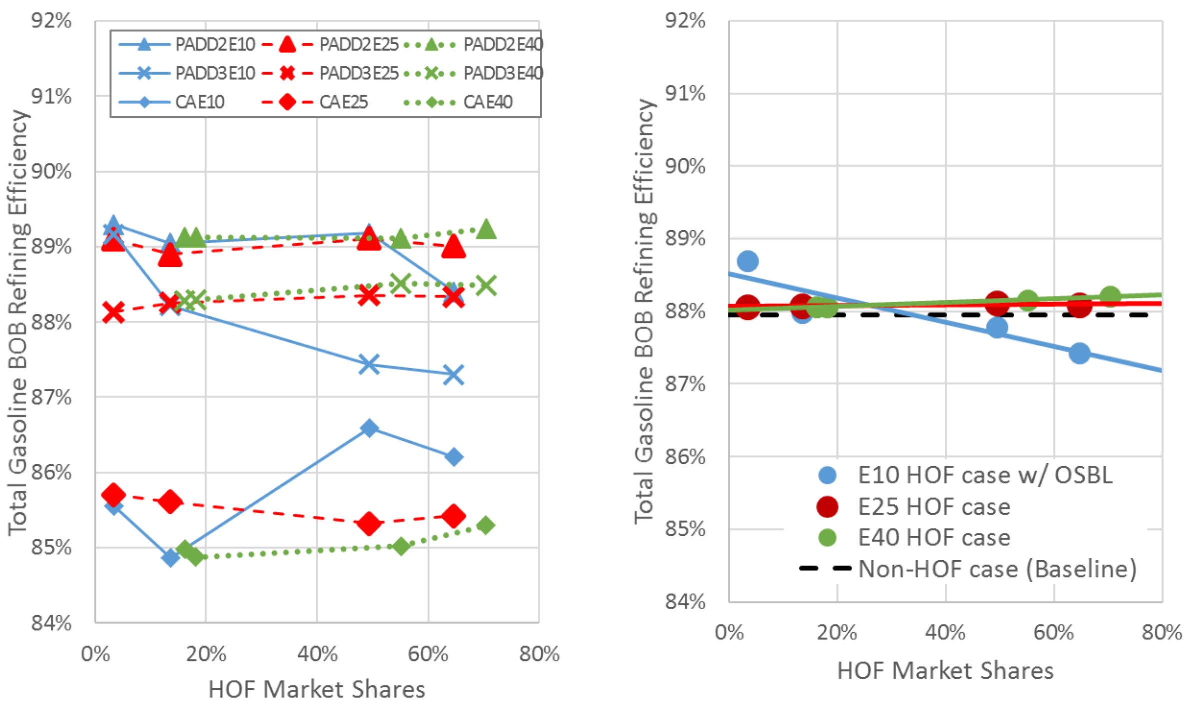
Among the ethanol blending level, HOF market share, and region, the regional impact is the most noticeable, especially between CA and PADDs 2 and 3. The regional impacts of HOF production is further discussed in Section 5.2.2. The overall refining efficiencies are fairly unchanged, but changes are seen in the ethanol blending levels and HOF market shares in the E25 and E40 HOF scenarios. On the other hand, the E10 HOF scenarios show the change in energy efficiency to be more sensitive to the HOF market shares (up to 0.7 percentage points) than for the E25 and E40 HOF scenarios (up to 0.3 percentage points). Note that all of the E10 HOF scenarios include the OSBL improvement, which results in a slightly higher refining efficiency at low HOF market shares than the efficiency in the basline non-HOF scenario. The results are generally consistent with the phase I study (Han et al. 2015).



(a) By region (b) Aggregated PADDs 2 and 3 and CA

Figure 13 Overall refining efficiency of the E10, E25, and E40 HOF scenarios versus HOF market shares (a) by region and (b) aggregated for PADDs 2 and 3 and CA

Figure 14 shows the refining efficiency of the total gasoline BOB pool of the E10, E25, and E40 HOF scenarios versus HOF market shares in PADDs 2 and 3 and CA as well as for the aggregated refining efficiency of these regions. The total gasoline BOB pool consists of domestic regular and HOF gasoline BOB as well as export gasoline. The refining efficiency of the total gasoline BOB pool of the E10, E25, and E40 HOF scenarios are 2.3–3.8, 2.2–3.6, and 1.7–3.5 percentage points, respectively, lower than the overall refining efficiency of each scenario shown in Figure 13. In the E10 HOF scenarios, the impact of HOF market shares on the change of total gasoline refining efficiency is more noticeable (up to 1.9 percentage points) than that of the overall refining efficiency (up to 0.7 percentage point). On the other hand, the ethanol blending levels and HOF market shares have only a small impact on the total gasoline pool's refining efficiency for the E25 and E40 scenarios, which is consistent with the phase I findings.

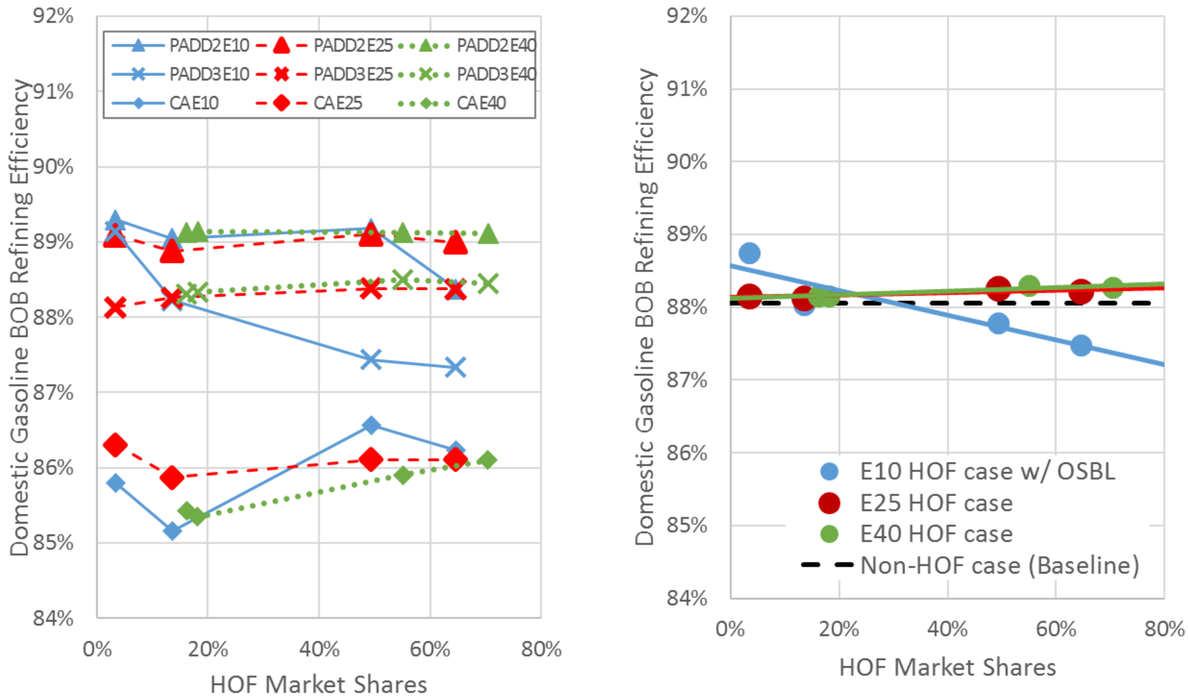


(a) By region (b) Aggregated PADDs 2 and 3 and CA

Figure 14 Total gasoline BOB refining efficiency of the E10, E25, and E40 HOF scenarios versus HOF market shares (a) by region and (b) aggregated for PADDs 2 and 3 and CA

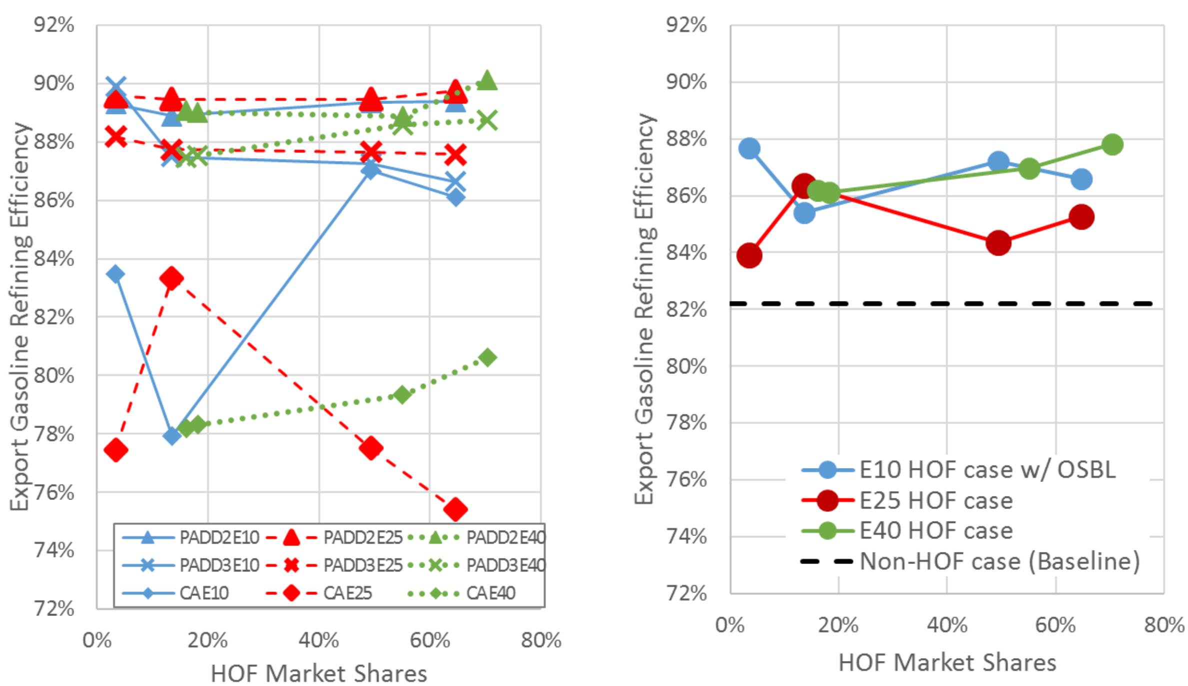
Figures 15 and 16 present the domestic and export gasoline refining efficiency of the E10, E25, and E40 HOF scenarios versus HOF market shares in PADDs 2 and 3 and CA as well as the aggregated refining efficiency of these regions. Here, the domestic BOB pool includes both regular and premium (e.g., HOF) gasolines. In PADDs 2 and 3, the differences in refining efficiencies between the total and domestic gasoline BOB and between the total gasoline BOB and export gasoline are less than 0.12% and less than 1.0%, respectively. Note that the export gasoline accounts for up to 15% of the total gasoline pool in PADDs 2 and 3. Because of the difference in the production volume, the differences in refining efficiencies between the total gasoline BOB and export gasoline is greater than that between the total and domestic gasoline BOBs.

In CA, however, the differences in refining efficiencies between the total and domestic gasoline BOBs and between the total gasoline BOB and export gasoline are much greater than those in PADDs 2 and 3, at less than 0.9% and less than 10%, respectively. Again, the greater difference in refining efficiencies between the total gasoline BOB and export gasoline than that between the total and domestic gasoline BOBs results from the small share of export gasoline in the total gasoline pool. For the largest difference in refining efficiencies between the total gasoline BOB



(a) By region (b) Aggregated PADDs 2 and 3 and CA

Figure 15 Domestic gasoline BOB refining efficiency of the E10, E25, and E40 HOF scenarios versus HOF market shares (a) by region and (b) aggregated for PADDs 2 and 3 and CA



(a) By region (b) Aggregated PADDs 2 and 3 and CA

Figure 16 Export gasoline refining efficiency of the E10, E25, and E40 HOF scenarios versus HOF market shares (a) by region and (b) aggregated for PADDs 2 and 3 and CA

and export gasoline refining efficiencies (10%) with E25 HOF in the 2030 HIGH scenario, the export gasoline share is only 6%.

The larger variations in refining efficiencies in the CA scenarios are caused by the greater shifts in gasoline pools relative to the PADDs 2 and 3 scenarios. Figure 17 shows the domestic gasoline BOB and export gasoline pools of the E25 HOF scenarios for PADDs 2 and 3 and CA. The E25 HOF scenarios are selected because the E25 HOF scenario with 2030 HIGH HOF market share provides the largest difference in refining efficiencies between the total gasoline BOB and export gasoline. As shown in the figure, the domestic gasoline BOB pool is generally consistent and the export gasoline pool changes gradually with the various HOF market shares. However, the domestic gasoline BOB pool in CA varies noticeably, and the changes in the export gasoline pool is dramatic, which results from a substantial shift of gasoline components between the two gasoline pools.

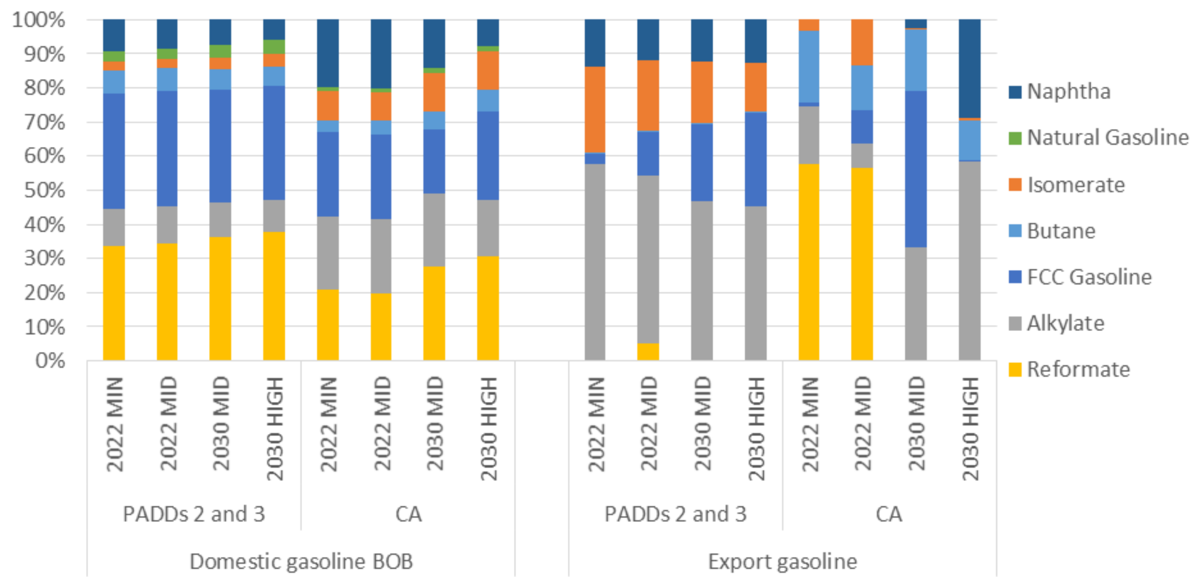
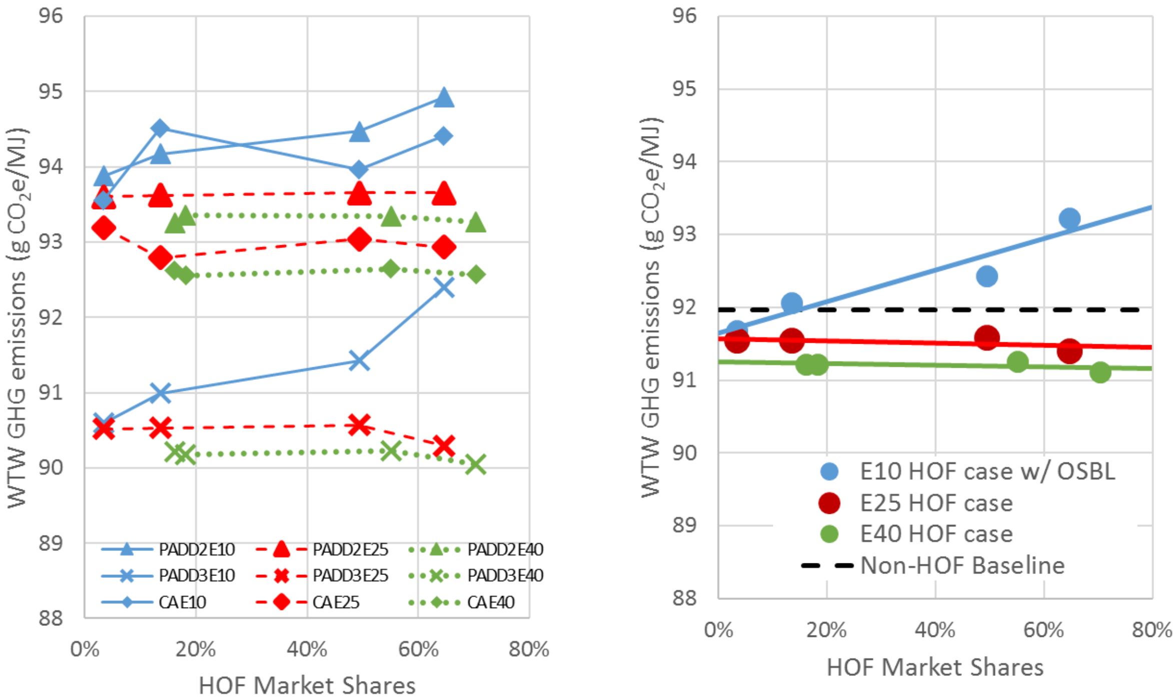


Figure 17 Domestic gasoline BOB and export gasoline pools of the E25 HOF scenarios for PADDs 2 and 3 and CA

Figure 18 provides the WTW GHG emissions (g CO_2e/MJ of HOF BOB) associated with BOB for E10, E25, and E40 HOF blending versus HOF market shares by regions and as an aggregate average of three major refining regions (e.g., PADDs 2 and 3 and CA). The WTW GHG emissions of HOF BOB is compared with those of regular gasoline in the non-HOF baseline scenario. Note that the baseline and HOF BOB include no ethanol. The aggregate averages of the WTW GHG emissions for HOF BOB for the E25 and E40 scenarios of three major refining regions are largely constant at 91.5 and 91.2 g CO_2e/MJ, respectively, and not significantly different from the baseline BOB values (92 g CO_2e/MJ). In other words, the impact of the E25 and E40 HOF production is negligible with respect to ethanol blending level and HOF market share. However, the aggregate averages of WTW GHG emissions of E10 HOF BOB of three major refining regions increase by 1.5 g CO_2e/MJ (i.e., from 91.7 to 93.2 g CO_2e/MJ) as HOF market shares increase.

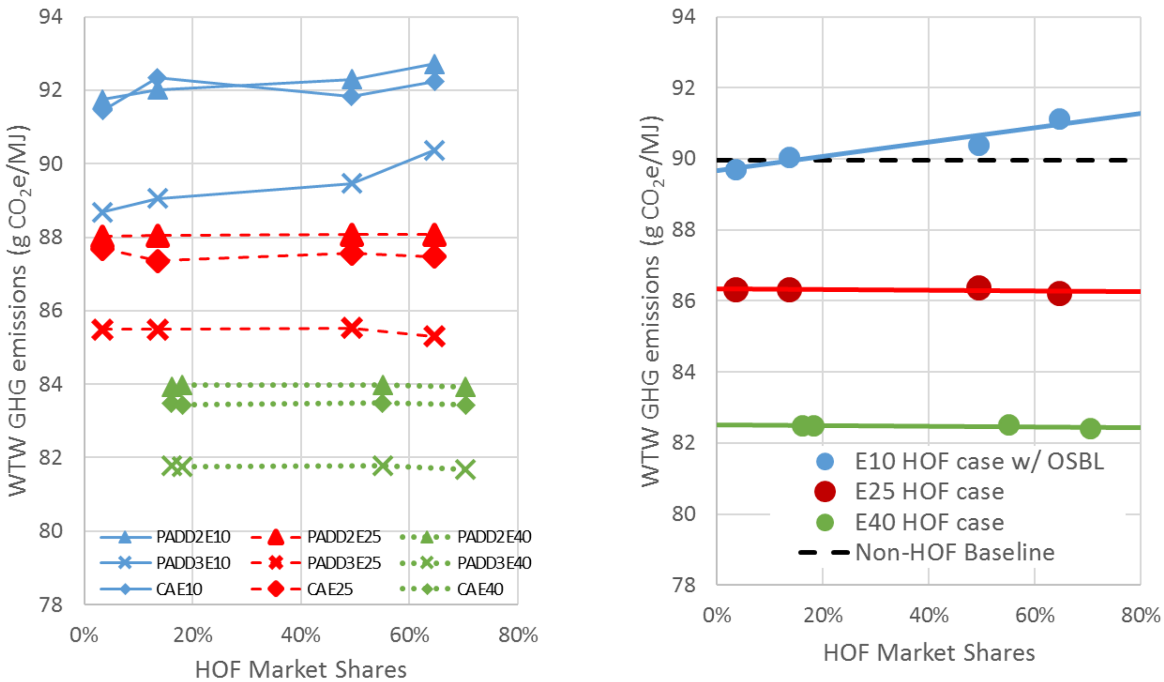


(a) By region

(b) Aggregated PADDs 2 and 3 and CA

Figure 18 WTW GHG emissions (g CO_2e/MJ of HOF BOB) associated with BOB production for E10, E25, and E40 HOF as compared with non-HOF baseline gasoline BOB (a) by region and (b) aggregated for PADDs 2 and 3 and CA

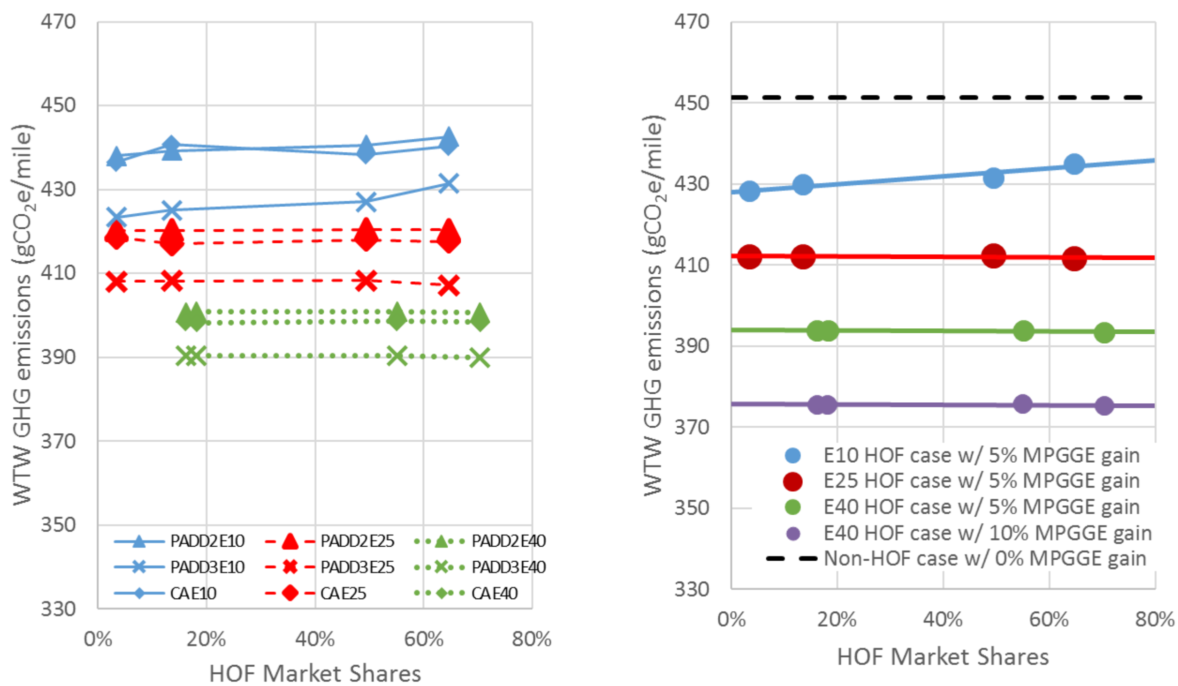
The impacts of HOF production on the WTW GHG emissions of finished gasoline (i.e., including ethanol) are even smaller, since the ethanol blending dilutes the impacts of HOF production. As shown in Figure 19, the WTW GHG emissions associated with HOF are dominated by the ethanol blending level. In the figure, we assume that the ethanol comes entirely from corn. With regard to corn ethanol blending, E10, E25, and E40 HOF provide a 0–1, 4, and 8% reduction, respectively, of WTW GHG emissions relative to baseline E10 gasoline, on a per-megajoule basis. With regard to corn stover ethanol blending, the GHG emissions reduction due to E10, E25, and E40 HOF increases to 5–6, 13, and 24%, respectively, due to the lower GHG emission intensities of corn stover ethanol. The reductions result largely from the GHG reductions of bioethanol relative to petroleum BOB, as discussed above.



(a) By region (b) Aggregated PADDs 2 and 3 and CA

Figure 19 WTW GHG emissions (g CO_2e/MJ of HOF) associated with E10, E25, and E40 HOF as compared with non-HOF baseline gasoline (corn ethanol is used blending with petroleum BOB) (a) by region and (b) aggregated for PADDs 2 and 3 and CA

Figure 20 presents GHG emissions in g CO_2e per mile driven by HOFVs fueled with E10, E25, and E40 HOF blended with corn ethanol by factoring vehicle efficiency difference of HOFVs versus non-HOFVs. The baseline in the figures denotes the WTW GHG emissions per mile driven by gasoline internal combustion engine vehicles fueled with E10 regular gasoline in the non-HOF baseline scenario. As mentioned earlier, a 5% mpgge gain for HOFVs is assumed, while the E40 HOF maximum scenario assumes a 10% gain. In the figure for individual regions, the results with only a 5% mpgge gain for HOFVs are presented for simplicity. Compared with the per-MJ results, the 5 and 10% mpgge gains provide additional reductions in WTW GHG emissions of about 4 and 9%, respectively, on per-mile basis. 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 scenarios are estimated at 4–5, 9, 13, and 17%, respectively, with corn ethanol. With corn stover ethanol, the WTW GHG emissions reductions increase to 9–10, 17, 28, and 32%, respectively.



(a) By region (b) Aggregated PADDs 2 and 3 and CA

Figure 20 GHG emissions (g CO_2e per mile driven) by HOFVs fueled with E10, E25, and E40 HOF as compared with regular gasoline vehicles in the non-HOF baseline scenario (a) by region and (b) aggregated for PADDs 2 and 3 and CA

5.2.2. Product-specific Energy Efficiency and GHG Emissions of Gasoline BOB for E25 HOF from Different Regions with the 2030 MID HOF Market Share

Petroleum refining efficiency varies by region because of the variations in crude quality (e.g., crude API gravity and sulfur content) and refinery complexity, among other factors (Elgowainy et al. 2014). Figure 21 shows the variation in overall refining efficiency by region, which can be explained mainly by the crude API gravity and conversion index in Table 6. The overall refining efficiency of PADDs 1 and 5 without CA is higher than that in the other regions because of the high API gravity and low conversion index in the former regions. On the other hand, the low refining efficiency of CA refineries results from its low API gravity and high conversion index. Note that the overall refining efficiency of PADD 4 is lower than that of PADD 1 even if the average crude quality and conversion index are similar to each other. The low efficiency in PADD 4 can be explained by its unbalanced crude slate, consisting largely of 50/50 between light shale oil and heavy oil sands without intermediate crudes.

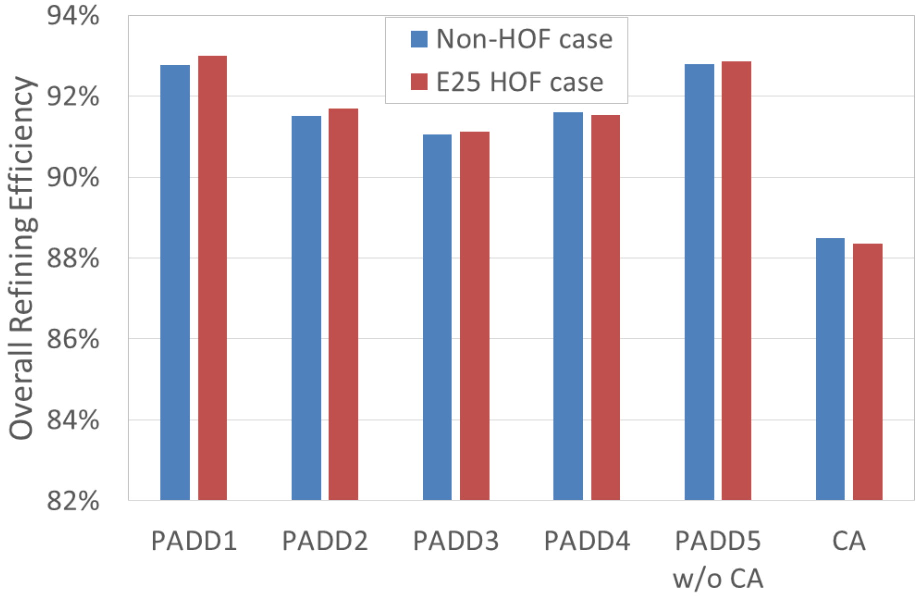


Figure 21 Overall petroleum refinery efficiency for the baseline non-HOF and E25 HOF scenarios by region

Figure 21 also shows that the impact of E25 HOF production on overall refining efficiency compared to E10 non-HOF scenario is minimal (<0.2%). Similarly, the impact of E25 HOF production on domestic gasoline refining efficiency is also negligible (<0.3%), as presented in Figure 22. The regional gasoline BOB efficiency pattern follows the regional pattern for the overall refinery efficiency.

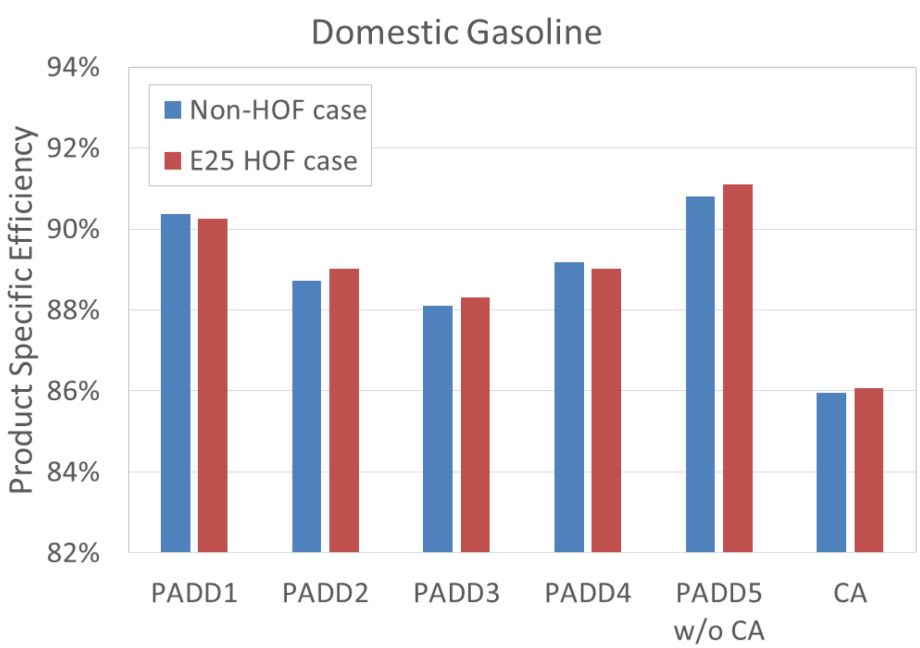


Figure 22 Domestic gasoline BOB refining efficiency for the baseline non-HOF and E25 HOF scenarios by region

As shown in Figure 23, the WTW GHG emission reductions by HOFVs fueled with E25 HOF relative to regular gasoline vehicles in the non-HOF scenario are fairly consistent throughout all regions (36–40 g CO_2e/mile driven). The reduction in the WTW GHG emissions is driven largely by the low GHG emissions associated with ethanol blendstock and the 5% vehicle efficiency gains. In the figure, corn ethanol is used for ethanol blending. The key driver for the regional differences in the WTW GHG emissions is the crude source, in addition to gasoline refining efficiency. For example, the WTW GHG emissions of PADDs 2 and 4, in which a large amount of oil sands is consumed, are greater than those of PADDs 1, 3, and 5 without CA. The WTW GHG emissions of E25 HOF in CA are higher than those in the other regions because of the low refining efficiency in the former.

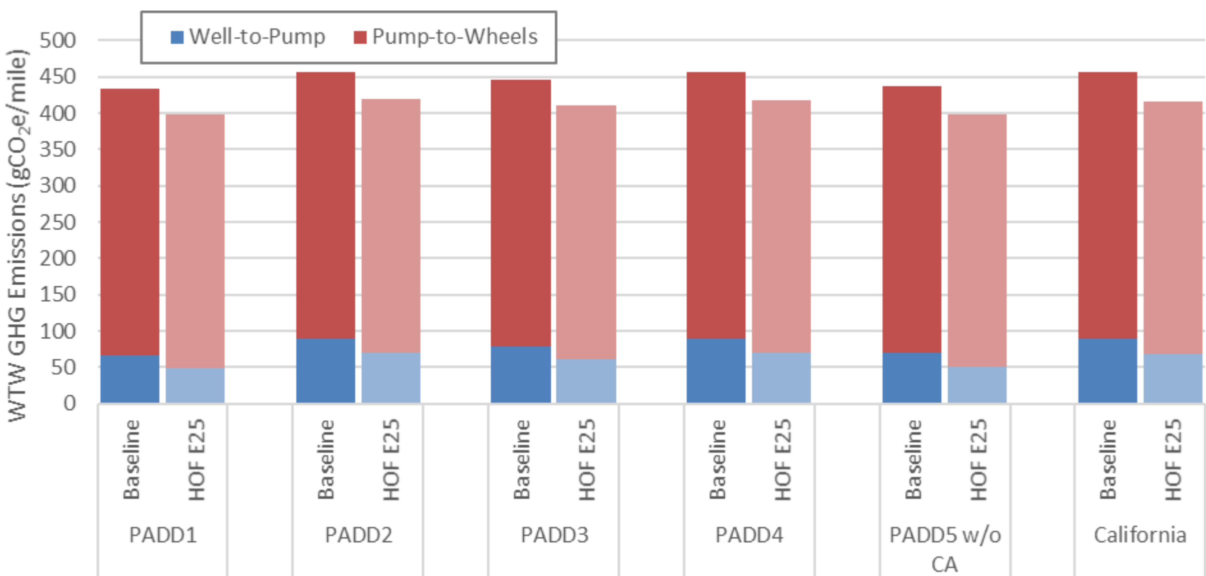


Figure 23 WTW GHG emissions (g CO_2e/mile driven) by HOFVs fueled with E25 HOF as compared with regular gasoline vehicles in the non-HOF baseline scenario by region (corn ethanol is assumed for ethanol blendstock)

5.2.3. Summary of WTW GHG Emissions Changes of HOF

The chart in Figure 24, similar to one presented in the phase I report, illustrates WTW GHG emission reductions by HOFVs fueled by HOF. The figure summarizes the GHG emission reductions of HOFVs with gains of 5 and 10% mpgge, ethanol blending, and changes in refinery operation with HOF BOB production estimated in this phase II analysis. The results show that the impacts of HOF introduction on WTW GHG emissions were dominated by vehicle efficiency gains resulting from the use of HOF and from higher ethanol blending levels. For example, the 5 and 10% mpgge gains by HOFVs reduced the WTW GHG emissions by 4 and 8%, respectively, relative to baseline E10 gasoline vehicles (brown bars). Additional 4 and 9% reductions in WTW

GHG emissions can be realized with E25 and E40 blending of corn ethanol, respectively (corn ethanol GHG reductions were simulated with GREET, as discussed above). With corn stover ethanol blending, the additional WTW GHG reductions, on top of vehicle efficiency gain effects, were 2, 12, and 23% for E10, E25, and E40, respectively, relative to the results of E10 baseline vehicles fueled by E10 regular gasoline with corn ethanol.

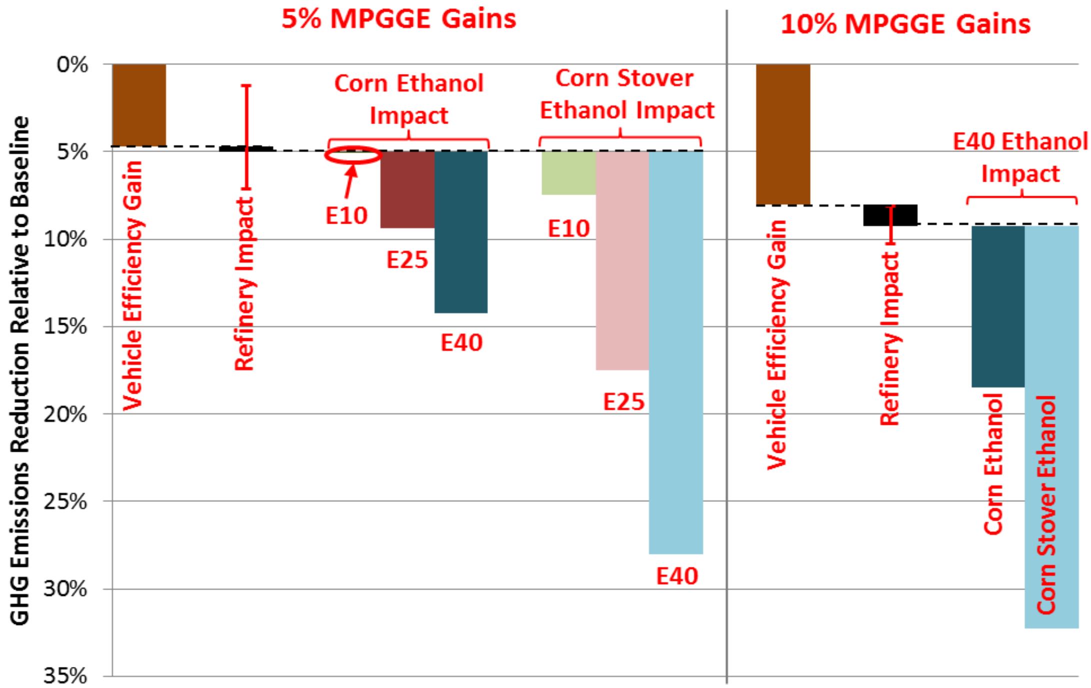


Figure 24 HOF-fueled HOFVs WTW GHG emission reductions relative to emissions of vehicles fueled by regular gasoline (E10) on per-mile basis

On the other hand, the production efficiencies of gasoline BOB for various HOF blend levels (E10, E25, and E40) had only a small impact on WTW GHG emissions (~1% reduction on average). Note that the black bar indicates the average of the refinery impacts of 39 HOF scenarios with three ethanol blending levels (E10, E25, and E40), four HOF market shares (2022 LOW, 2022 MID, 2030 MID, and 2030 HIGH), three major regions (PADDs 2 and 3 and CA), and three minor regions (PADDs 1, 4, and 5 without CA) with E25 MID scenario in 2030. The error bars denote the maximum and minimum impacts by GHG emission results among the 39 HOF scenarios.

The WTW analysis shows that ethanol can be a major enabler in producing 100-RON HOF with vehicle efficiency gains. In addition, with lower GHG emissions intensity of ethanol relative to gasoline BOB, blending of ethanol into gasoline with higher blending level (e.g., E25 and E40) brings additional reductions in WTW GHG emissions. Note that these results from aggregate refinery LP models used in the phase II study are generally consistent with those from configuration refinery LP models used in Han et al. (2015).

5.3. Sensitivity Analysis for Key Parameters

To examine the impact of key parameters on the WTW GHG emissions of HOF, this study conducted sensitivity analyses on price spreads between regular gasoline and naphtha and between crude types.

5.3.1. Sensitivity Analysis on Price Spreads Between Regular Gasoline and Naphtha

To produce HOF, additional octane is required in the system, which can come from ethanol. Another way of increasing the octane number is to remove—or sell—low-octane components. Naphtha conceivably could be "excessed" from the refining system to balance a high HOF demand. Note that this naphtha price analysis is not intended to project a break-even price with respect to blending or exporting naphtha. Rather, the price change is intended to drive naphtha movements with respect to maintaining HOF production.

The baseline scenario for this sensitivity analyses is an aggregate model for E25 HOF in PADDs 2 and 3, as developed in Section 3. The HOF market penetration shares are set to 49% from the E25 HOF MID scenario in 2030. In the baseline scenario, the naphtha sales volume is constrained at about 470 kBPD and the naphtha price is set to 15 cpg less than the domestic regular CG. In the sensitivity analysis scenarios, the naphtha sales were not constrained, and three discounting prices relative to the domestic regular CG price were used: 15 cpg (same as the baseline scenario), 35 cpg, and 45 cpg.

Figure 25 presents the impacts of naphtha prices on naphtha sales and total gasoline volumes in MBPD. When the constraint on the naphtha sales volume is removed at the baseline naphtha price (15 cpg less than the gasoline price), the naphtha sales volume increases significantly. The increased naphtha sales volume is derived from the reduced export gasoline volume and the increased crude inputs as shown in Figure 26. When naphtha is priced at a deep discount to gasoline (at 45 cpg less than the gasoline price), naphtha sales drop considerably to about 300 kBPD, which is similar to the naphtha sales volume in the baseline scenario. This drop in the naphtha sales is offset by other operating factors, including a reduction in crude throughput and an increase in export gasoline from the excess naphtha within the refinery that sold the naphtha.

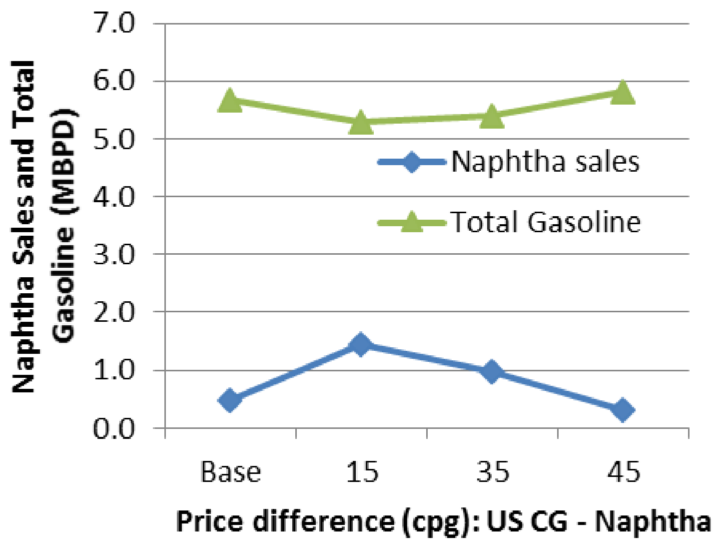
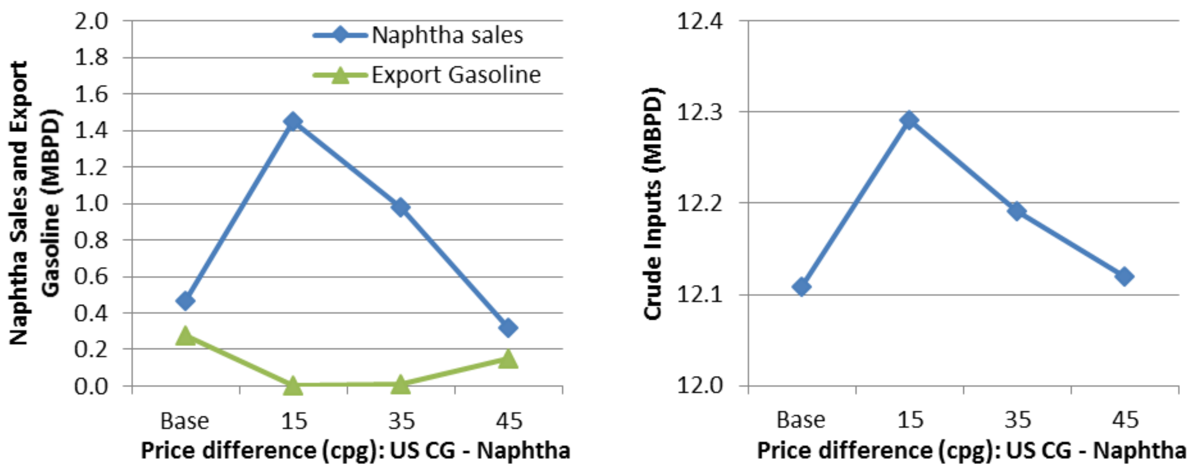


Figure 25 Impacts of naphtha prices difference on naphtha sales and total gasoline volumes (MBPD)



(a) Export gasoline

(b) Crude inputs

Figure 26 Impacts of naphtha price difference on export gasoline and crude input volumes (MBPD)

Since the increased naphtha sales volume reduces the burden of meeting the RVP standards, it increases the overall and gasoline refining efficiencies up to 1.2 percentage points, as shown in Figure 27. As naphtha sales decreased, the gasoline BOB efficiencies for HOF production also decrease since more energy intensive conversion of naphtha to finished gasoline is required. Similarly, when the naphtha sales constraint is removed, the WTW GHG emissions of HOF BOB is reduced by 1.0 g CO_2e/MJ (Figure 28). The reduction decreases as the naphtha sales price increases.

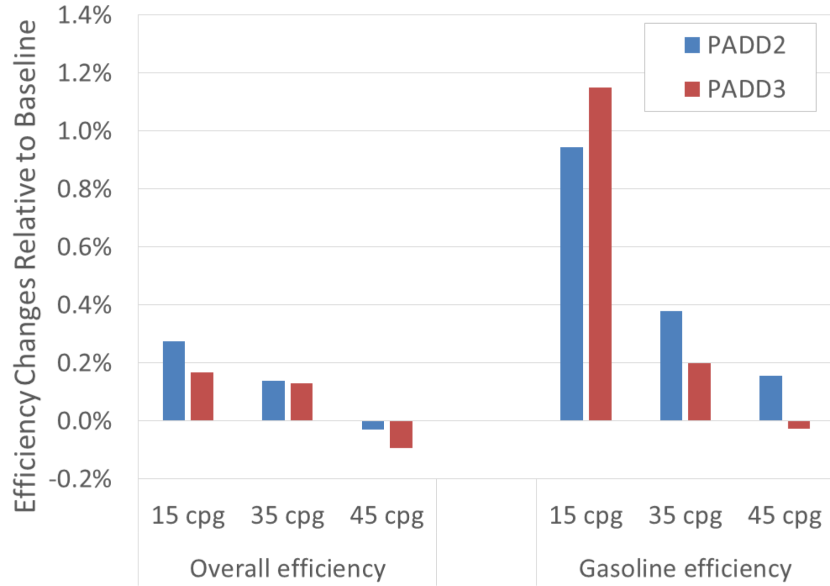


Figure 27 Impacts of naphtha price difference on the overall and total gasoline BOB refining efficiencies

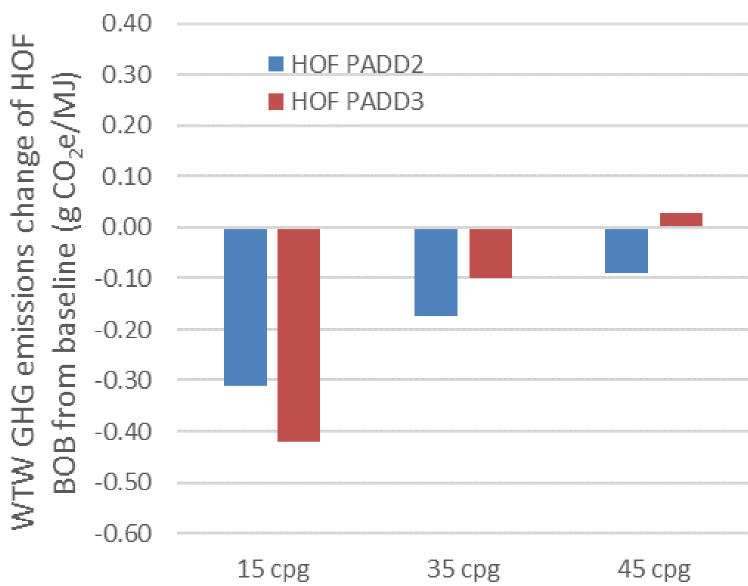


Figure 28 Impacts of naphtha price difference on the WTW GHG emissions of HOF BOB (g CO_2e/MJ BOB)

5.3.2. Sensitivity Analysis on Crude Type

In this sensitivity analysis, the crude slate was changed to increase or decrease the crude feed API gravity. This can be accomplished many ways, but in this study, the Low API gravity scenario was developed with an increase in heavy Canadian crude, and the High API gravity scenario was developed with an increase in the LTO crude. The baseline scenario for this sensitivity analyses is an aggregate model for E25 HOF in PADDs 2 and 3, as developed in Section 3. The HOF market penetration shares are set to 49% from the E25 HOF Mid scenario in 2030. The difference in API gravity and sulfur content between the High and Low API gravity scenarios is approximately 3 points and 0.4 percentage point in PADD 2 and 3.1 points and 0.3 percentage point in PADD 3, respectively (see Table 16).

Table 16 Key parameters in the sensitivity scenarios with crude type changes

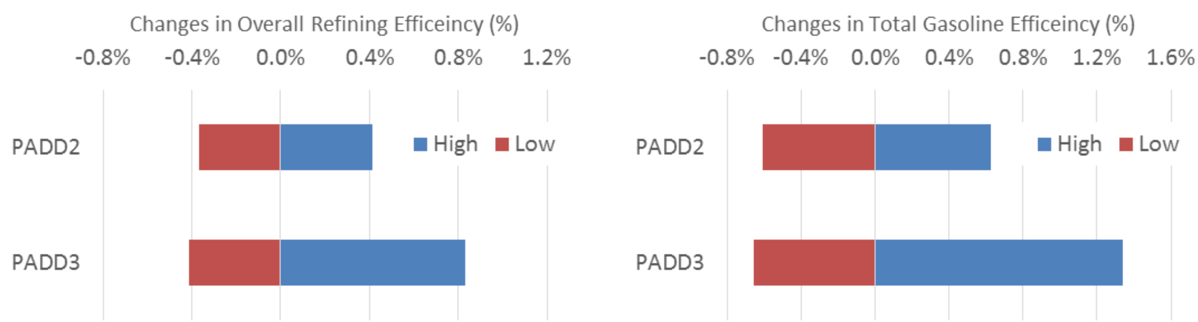
Parameter (unit)	PADD 2			PADD 3		
Crude type (represented by API gravity)	Low API gravity	Base API gravity	High API gravity	Low API gravity	Base API gravity	High API gravity
Crude API gravity	31.3	32.7	34.3	29.9	31.6	33.0
Crude sulfur (%)	1.6	1.4	1.2	2.1	2.0	1.8
Crude vacuum residue (%)	19.0	17.3	15.6	22.6	20.9	19.3
Conversion index	0.46	0.44	0.41	0.58	0.55	0.52
FCC throughput (kBPD)	851	796	777	2,360	2,297	2,230
Coker throughput (kBPD)	523	436	381	1,613	1,459	1,360
Reformer throughput (kBPD)	561	566	585	1,340	1,417	1,348
Reformer severity	95.6	95.6	95.8	95.0	95.0	96.7
Sev. x kBPD	54	54	56	127	135	130
Alkylation throughput (kBPD)	217	205	195	417	390	388
Total gasoline volume (kBPD)	1,538	1,515	1,509	3,211	3,210	3,162

Heavier crude tends to have higher conversion requirements compared to lighter crude. In this scenario, the forecasted crude and product slate are set as the basis. With this basis, a system will almost always require additional conversion to achieve the same material balance using a lower API gravity crude slate. Table 16 shows comparisons between the scenarios. As API gravity increases (i.e., the crude becomes lighter), the following occurs:

1. Crude sulfur content and vacuum residue content decrease, which results in less processing, as indicated by the lower conversion index.
2. FCC and coker throughputs decrease due to a lower vacuum residue share.
3. Alkylation throughput decreases, since fewer olefins are is available from FCC. Since FCC is a major producer of gasoline components, the total gasoline production decreases slightly.

Note that the base API gravity scenario has the highest reformer throughput in PADD 3. With both the Low and High API gravity scenarios, the E25 HOF target production (49%) is still achieved. Overall, with the more severe upgrading required on the Low API gravity scenario, the energy requirement is higher when processing low API gravity crude.

Figure 29 illustrates the impacts of crude type on overall and total gasoline refining efficiencies. The 3-point change in API gravity coupled with a 0.4-perentage-point change in sulfur content results in approximately 1% change in the overall refining efficiency. Note that the impact of crude type is not linear in PADD 3, which is caused by the non-linear reforming throughput in the refining region.



(a) Overall refining efficiency (b) Total gasoline efficiency

Figure 29 Impacts of crude type on overall and total gasoline refining efficiencies

Figure 30 presents the impacts of crude type on WTW GHG emissions of HOF BOB. The results are consistent with the total gasoline refining efficiency results. Note that the Low API gravity scenario takes into account the higher GHG emission intensity of the crude recovery due to the higher share of oil sands compared to the baseline and High API gravity scenarios.

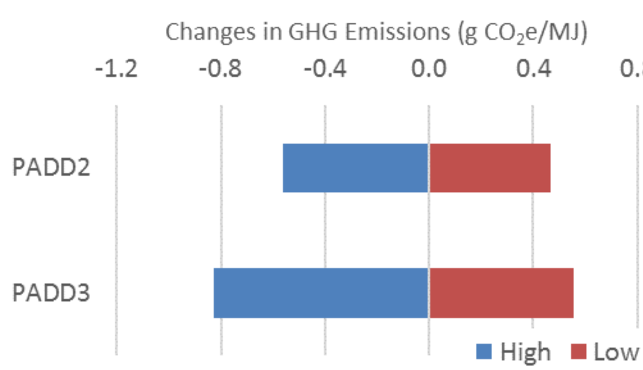


Figure 30 Impacts of crude type on WTW GHG emissions of HOF BOB (g CO_2e/MJ BOB)

6. GHG and Cost Impacts of Refinery Expansion Options for E10 HOF

The phase I study showed that, without the use of higher-ethanol blends such as E25 and E40, petroleum refineries would face a significant challenge to meet the high demand created by significant HOF market penetration (e.g., over 25% of the gasoline market) because of the heightened constraints on RON and RVP (Han et al. 2015). In particular, refineries with no or small deep conversion processing units (e.g., coking, catalytic cracking, hydrocracking, catalytic reforming, alkylation, and isomerization) would have a limited ability to produce a sufficient amount of high-RON and low-RVP blendstock. Thus, to increase the amount of HOF with an E10 blend, refinery expansion becomes necessary.

6.1. Refinery Expansion Options for E10 HOF Scenarios

This study investigated several refinery expansion options to increase the volume of high-octane components, including (1) an OSBL improvement, (2) the addition of an isomerization unit, (3) the expansion of an alkylation unit, and (4) the upgrade of a reformer from SRR to CCR. Details are as follows:

1. The OSBL improvement in this study includes splitters, pumps, piping, and storage for enhanced blending flexibility. One of the key benefits of the OSBL improvement assumed in this study is the splitting and segregation of light and heavy reformate in the different gasoline pools. The heavy reformate has higher RON (as well as MON and AKI) and lower RVP than the light reformate. Thus, the capability to segregate and optimize the blending of these two streams in the HOF and non-HOF pools is an important operational strategy at high volumes of E10 HOF.
2. The addition of an isomerization unit points to a broader issue of controlling light naphtha to produce a high volume of E10 HOF. While the volume and quality of light naphtha feeding an isomerization unit is dependent on the crude slate, light naphtha has low RON and high RVP relative to other gasoline components, which are undesirable characteristics. Compared to the feed naphtha, the isomerate has higher RON and higher RVP. The refinery has to re-balance the blending, including RVP control. One way of achieving this is by keeping the heavy FCC naphtha in the gasoline pool instead of the diesel pool because the heavy FCC naphtha has low RVP. Another approach is to add more reformate, which has low RVP.
3. The expansion of an alkylation unit is intended to produce additional alkylate, which has high RON and low RVP relative to other gasoline components, by increasing the C5 olefin feed to the alkylation unit from the FCC, which can be accomplished using a ZSM-5 catalyst. Two types of alkylation units are widely used: hydrofluoric (HF) and sulfuric acid alkylation units. Alkylate from a sulfuric alkylation unit is about 0.5 octane numbers higher than that from an HF alkylation unit. However, the impact of increasing alkylation

is expected to be limited because higher olefin production in the FCC results in lower gasoline yield to some extent. Thus, the overall quality and quantity increase in alkylate gasoline blendstock may not be sufficient to increase E10 HOF production.

4. The upgrade of a reformer from SRR to CCR can be a very effective solution for high volumes of E10 HOF because CCR can run at a higher severity and have better liquid yields than SRR. Note that reformate is often the highest-octane C5+ liquid component by volume in the HOF gasoline pool. Reformate also has low RVP, and is considered a heavy component in the gasoline pool. However, a key downside of reformate is that at high volume fractions, it can result in a heavy gasoline, which is constrained by DI. DI describes how an engine starts, warms up, and runs. DI is defined as a weighted sum of the ethanol content and the temperatures at which 10%, 50%, and 90% of the fuel is evaporated (denoted as T10, T50, and T90, respectively), as shown in the following formula for E10:

$$DI\ (^\circ F) = 1.5 \times T10 + 3.0 \times T50 + T90 + 2.4 \times (\text{ethanol content by volume})$$

   ASTM standard D4814 specifies that the DI of summer gasoline needs to be lower than 1,250°F. Thus, the gasoline pool needs to be balanced to meet the octane, vapor pressure, and endpoint (driveability) specifications. Heavy gasoline components, such as heavy reformates (~1,600°F), FCC gasoline (~1,500°F), alkylate (~1,200°F), and light reformate (~1,100°F), have higher DI than light gasoline components, such as isomerate (~750°F). Therefore, isomerate can potentially offer relief for DI.

6.2. Refinery LP Simulation Results of Refinery Expansion Options for E10 HOF Scenarios

Configuration models are appropriate to address WTW GHG emission impacts and associated costs for refinery expansion options, since the refinery expansion decisions would be made for individual refineries rather than for all refineries in an aggregated region uniformly. Also, individual refineries can have different combinations of process units, which impact the existing capacity of producing high-octane components. To examine the impact of the refinery expansions to refineries with different existing capacities, this study developed two configuration models (i.e., the high- and low-octane configuration models) for USGC medium coking refineries. The key process units for the two configuration models are summarized in Table 17 (Base column). In the high-octane configuration, CCR is utilized for a reformer, combined with an isomerization unit and a sulfuric acid alkylation unit. For the low-octane configuration, SRR is utilized for a reformer, combined with an HF alkylation unit but no isomerization unit. Since summer gasoline is more challenging to produce compared to winter gasoline, mainly due to the high winter RVP allowance, these two configuration models were set up for summer season simulations.

Table 17 Process units for the baseline and the refinery expansion scenarios

Process unit	Low-octane refinery					High-octane refinery		
	Base	OSBL	OSBL+ ISOM	OSBL +ALK	OSBL +CCR	Base	OSBL	OSBL +ALK
OSBL improvement	No	Yes	Yes	Yes	Yes	No	Yes	Yes
Isomerization	No	No	Yes	No	No	Yes	Yes	Yes
Alkylation	HF	HF	HF	HF+ZSM5	HF	SA	SA	SA+ZSM5
Reformer	SRR	SRR	SRR	SRR	CCR	CCR	CCR	CCR

As shown in Table 17, this study examined four refinery expansion options: (1) an OSBL improvement (OSBL), (2) adding isomerization with an OSBL improvement (OSBL+ISOM), (3) increasing alkylation and olefins from ZSM-5 with an OSBL improvement (OSBL+ALK) and (4) replacing SRR with CCR in addition to an OSBL improvement (OSBL+CCR). Because the high-octane refinery has an isomerization unit and CCR in the base scenario, these two refinery expansion options are considered only for the low-octane refinery.

Table 18 presents the total gasoline production and RFG and HOF production shares in the total gasoline pool for the refinery expansion scenarios. The analysis on the refinery expansion options was intended to estimate how much E10 HOF can be produced using the existing configurations and refinery expansion options. Neither export gasoline nor naphtha sales are allowed. The low-octane refinery does not produce any E10 HOF gasoline with the existing configuration. With the existing configuration, the high-octane refinery can produce about 38% HOF. However, the high-octane refinery produces only CG (i.e., no RFG production) because the refinery cannot produce a sufficient amount of low-RVP components.

Table 18 Total gasoline production and RFG and HOF production shares under the refinery expansion scenarios

Production share	Low-octane refinery					High-octane refinery		
	Base	OSBL	OSBL+ ISOM	OSBL +ALK	OSBL +CCR	Base	OSBL	OSBL +ALK
Total gasoline (kBPD)	53.0	52.9	50.4	54.3	45.2	54.9	54.1	54.3
RFG share	21%	20%	20%	20%	3%	0%	20%	20%
HOF production share	0%	25%	42%	33%	48%	38%	68%	72%
HOF RFG share (as in total HOF)	N/A	1%	20%	1%	0%	0%	20%	20%

In the low-octane refinery, the OBSL improvement increases the total HOF production share from 0 to 25%, while it increases the total HOF production share in the high-octane refinery from 38 to 68%. Additionally, the HOF RFG share in the total HOF in the high-octane refinery increases to 20%, while the HOF RFG share in the total HOF is still 1% in the low-octane refinery. For both low- and high-octane refineries, the total HOF increase with OSBL is 25–30% above the base scenario.

The most beneficial refinery expansion option for the low-octane refinery is the addition of the isomerization unit, which increases the total HOF production share to 42% and the HOF RFG share in the total HOF to 20%. The addition of the isomerization unit increases the RON of the total gasoline pool by replacing the naphtha with isomerate. Table 19 shows that the naphtha share decreases from 13 to 3% in the total gasoline pool and from 17 to 4% in the regular gasoline pool. This replacement of naphtha with isomerate increases the RON in the regular gasoline pool, which makes alkylate and reformate available for the E10 HOF pool. As shown in Table 19, the share of alkylate and reformate used in the E10 HOF pool increases by 74 and 18%, respectively.

Table 19 Gasoline pool compositions and the destination of alkylate, reformate, and FCC gasoline for the refinery expansion scenarios (%)

	Low-octane refinery					High-octane refinery		
Component	Base	OSBL	OSBL+ ISOM	OSBL +ALK	OSBL +CCR	Base	OSBL	OSBL +ALK
Total gasoline								
Butane	2	1	1	1	1	2	1	1
Natural gasoline	0	0	0	0	0	0	0	0
Alkylate	21	22	13	26	25	20	14	16
Reformate	33	30	33	29	31	28	40	41
FCC gasoline	32	33	39	30	32	36	33	30
Isomerate	0	0	11	0	0	5	12	12
Naphtha	13	13	3	12	11	8	0	0
Alkylate destination								
HOF	0	0	74	0	0	34	87	94
Regular	100	100	26	100	100	66	13	6
Reformate destination								
HOF	0	53	71	69	92	100	77	79
Regular	100	47	29	31	8	0	23	21
FCC gasoline destination								
HOF	0	26	21	40	63	0	69	71
Regular	100	74	79	60	37	100	31	29

Incremental alkylates from higher olefins via ZSM-5 have a small impact on the E10 HOF production share. For the low- and high-octane refineries, the HOF production share increases from 25 to 33% (by 8 percentage points) and from 68 to 72% (by 4 percentage points), respectively. The small impact can be explained by the small volume of FCC C4 olefins available for alkylation and the low alkylate yields. C4 alkylate is 5 points higher in (R+M)/2 than C3 and C5 alkylates, and 1 psi lower in RVP than C3 alkylate, making C4 olefins the preferred alkylate feed. ZSM-5, while increasing overall olefin yields from FCC, is more selective to produce C3 olefins (about 2.5 times higher than C4 olefins), often targeted to sell into the propylene markets versus alkylation. Note that while C5 alkylate could be used for RVP control because of its lower RVP than C4 alkylate (by 2 psi), C5 alkylation is not as common as C3 or C4 alkylation. Additionally, the higher olefin yield by ZSM-5 will decrease the full-range FCC naphtha yield to the pool as mentioned above.

Replacing SRR with CCR provides the most significant increases in the HOF production share, from 25 to 48% (Table 18). However, the CCR does not increase the RFG share in the total HOF. In fact, the RFG share in the total gasoline is reduced from 20 to 3%. In this refinery expansion scenario, a key fuel specification is DI. With the upgraded reformer, heavy naphtha is routed to the reformer, which increases the RON by about 30 points. However, the production is limited up to a heavy distillation specification. Thus, the naphtha reduction in this reformer upgrade is not as effective as that in the addition of an isomerization unit, which constrains the re-balancing of the gasoline pools.

Note that the impacts of the refinery expansion options are specific to the baseline configuration models developed for this study. As the results depend largely on re-balancing the existing gasoline pool into a new pool with a given refinery expansion, the impacts could be different by the configuration of the baseline refinery. For example, some refineries have the capability of segregating streams for more selective blending procedures. Thus, the OSBL improvement may not be applicable to these refineries. Also, some refineries start from a higher octane potential than others, since they already have large reformers, alkylation units, or isomerization units. Thus, those refineries may not require process unit expansion.

6.3. Energy Efficiency and WTW GHG Emissions of HOF Gasoline with Refinery Expansion Options

Figure 31 shows the impact of refinery expansion options on overall and total gasoline refining energy efficiencies. The overall and total gasoline refining energy efficiencies are reduced from the baseline refinery efficiencies by less than 0.5 and 1%, respectively. These results are consistent with the findings in Elgowainy et al. (2014) that a more complex refinery consumes additional energy. Compared to the high-octane refinery, the low-octane refinery is more sensitive to refinery expansion. A key observation from this energy efficiency result is the relationship between energy efficiency and alkylate shares. As pointed out in Elgowainy et al. (2014) and Han et al. (2015), alkylation is typically more energy-intensive than other processes. Note that the OSBL improvement lowers the alkylation throughput for the high-octane refinery from 12.6 kBPD in the base scenario to 8.3 kBPD in the OSBL scenario, which helps increase the energy efficiency slightly by 0.1 and 0.4%, respectively, for the overall and total gasoline refining efficiencies. Conversely, a larger alkylation throughput in the OSBL+ALK scenario lowers the energy efficiency relative to the OSBL scenario for both low- and high-octane refineries.

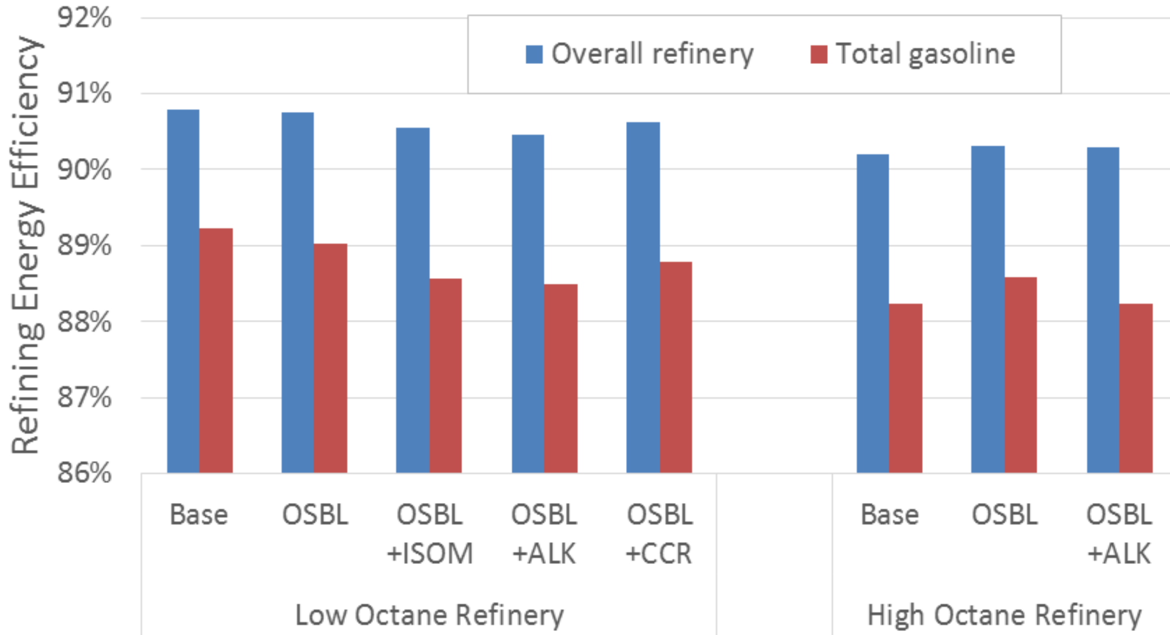


Figure 31 Impact of refinery expansion options on overall refinery and total gasoline energy efficiency

In Figure 31, the total gasoline consists of E10 regular gasoline and E10 HOF. To see the impacts of refinery expansion options on each of the gasoline pools, Figure 32 provides the impact of refinery expansion options on regular gasoline and HOF refining efficiencies separately. The HOF refining efficiency for the base scenario in the low octane refinery is not presented in the figure because the low octane refinery does not produce E10 HOF. When these two gasoline grades are separated, their refining efficiencies vary widely because of significant shifts in the gasoline pools. For example, in the OSBL+ISOM scenario, a significant shift of the alkylate share in the regular gasoline pool occurs because isomerate pushes alkylate from the regular gasoline pool into the HOF pool. Because of the high energy intensity of alkylate, the low alkylate share in the regular gasoline pool helps increase the regular gasoline refining efficiency. Conversely, in the OSBL+ALK scenario, the increased alkylate is pooled with regular gasoline, which lowers the regular gasoline refining efficiency. Similar to the export gasoline in the baseline HOF scenarios, the changes in the regular gasoline refining efficiencies and alkylate shifts may arguably be attributed to HOF production. Thus, we allocate the additional energy intensity in the regular gasoline pool to the corresponding HOF BOB pool for each of the HOF scenarios for the WTW GHG emissions.

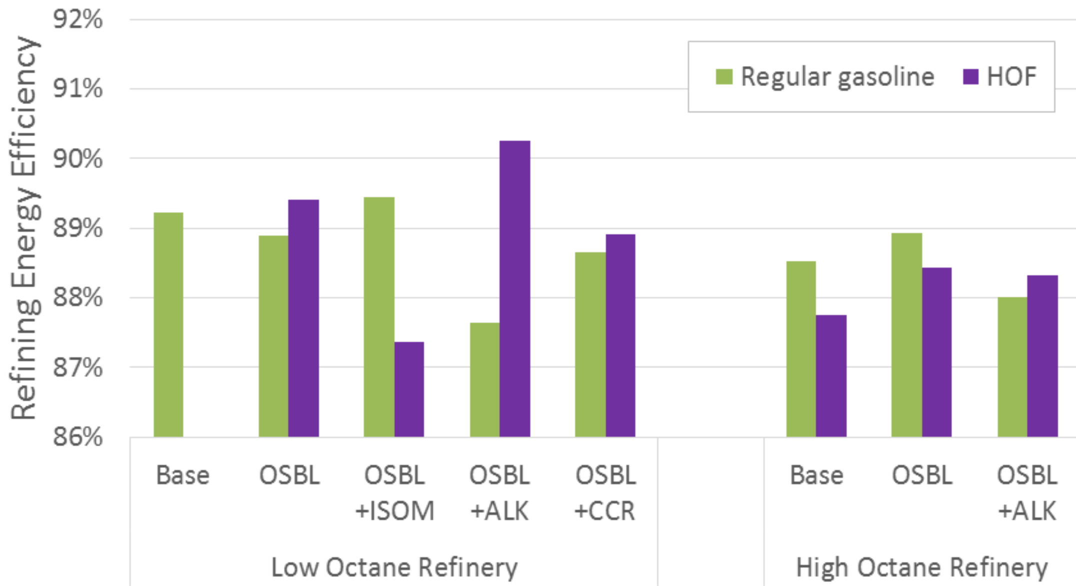


Figure 32 Impact of refinery expansion options on regular gasoline and HOF refining energy efficiency

Figure 33 presents the impact of refinery expansion options on the unadjusted and adjusted WTW GHG emissions of E10 HOF BOB. The unadjusted WTW GHG emissions are based on the HOF BOB energy efficiencies in Figure 32. As mentioned previously, the adjusted WTW GHG emissions for HOF take into account the incremental WTW GHG emissions of regular gasoline for each option relative to the base option. The key driver for this adjustment is the shift of alkylate shares in the two gasoline pools (regular and HOF). As mentioned previously, the OSBL+ISOM scenario produces additional isomerate, which shifts alkylate from the E10 regular BOB pool to the E10 HOF BOB pool. This shift of alkylate arbitrarily increases the GHG emissions of the E10 HOF BOB and lowers those of the E10 regular BOB because of the high GHG emission intensity of alkylate. Once the incremental WTW GHG emissions of regular BOB for each scenario relative to the base scenario is adjusted to those of HOF BOB, the WTW GHG emissions of HOF BOB in the OSBL+ISOM option are reduced by 0.6 g CO_2e/MJ BOB in the low-octane refinery.

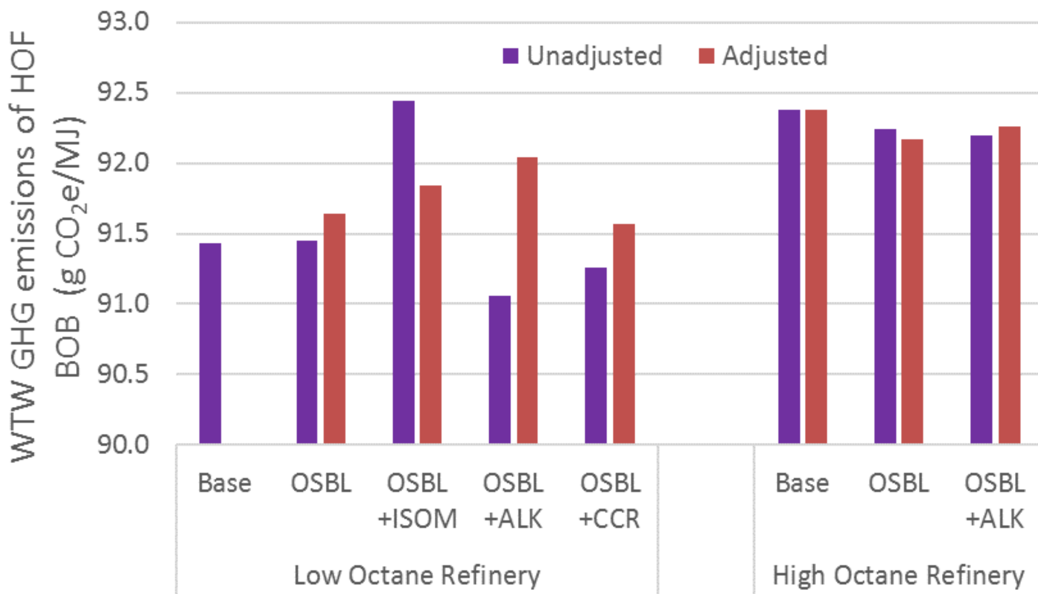


Figure 33 Impact of refinery expansion options on WTW GHG emissions of E10 HOF BOB

On the other hand, the additional alkylate is pooled with regular gasoline in the OSBL+ALK option, which increases the GHG emissions of regular BOB arbitrarily. Thus, with the adjustment, the GHG emissions of E10 HOF BOB in the OSBL+ALK option are increased by 1.0 g CO_2e/MJ BOB in the low-octane refinery. Overall, the impact of the refinery expansion options on the adjusted WTW GHG emissions of HOF BOB are not significant, less than 0.6 and 0.2 g CO_2e/MJ BOB, respectively, for the low- and high-octane refineries. However, it is important to note that the small increases in the WTW GHG emissions of E10 HOF BOB with refinery expansions are valid under specific conditions and at limited HOF penetration (e.g., 42% with OSBL+ISOM in the low-octane refinery). A higher HOF penetration could require substantially more energy. For example, once OSBL+ISOM is implemented at the low-octane refinery, the next available refinery expansion options to increase the HOF share over 42% would be more energy- and cost-intensive. Thus, these results can neither be extrapolated to nor directly compared with the results from studies that assume higher HOF penetrations, such as Hirshfeld et al. (2014).

6.4. Estimation of Costs Associated with Increased HOF Production

These refinery expansion options are associated with the increases in cost of gasoline products. To estimate the costs associated with increased HOF production, this study examined the incremental capital and fixed costs in the OSBL and the OSBL+ISOM options. Note that the OSBL+ISOM option is the most promising refinery expansion option for the low-octane refinery. Also, this cost estimation is not actual market costs of these refinery expansions but rather approximation of costs based on our understanding of the industry. For example, this study assumed that an OSBL improvement, including splitters, pumps, piping, and storage, would cost approximately $20 million for a 100-kBPD refinery. Also, the cost of an isomerization unit for a 100-MPBD refinery in USGC is approximately $64 million.

Amortizing this cost depends on the financial parameter assumptions, and two bases were chosen: 5% return on investment (ROI) after tax and 10% ROI after tax. The capital cost is amortized on the basis of 10-year recovery, 37% tax rate, 70% equity investment, and 6.5% interest rate. This is divided by the total production volume of gasoline. Typically, incremental fixed costs are associated with new process units, such as operators for the isomerization unit, maintenance requirements, taxes, insurance, and administrative costs. This study assumes no incremental operating expenses for the OSBL upgrades. As summarized in Table 20, the cost of the OSBL improvement for more selective blending is approximately 0.4 cpg or less. If isomerization is chosen in addition to the OSBL improvement, this cost ranges from 1.6 to 2.2 cpg.

Table 20 Capital and incremental fixed costs of the OSBL and OSBL+ISOM scenarios (cpg of total gasoline volume)

	5% ROI assumption		10% ROI assumption	
Cost category	OSBL	OSBL+ISOM	OSBL	OSBL+ISOM
Capital cost	0.3	1.3	0.4	1.9
Incremental fixed cost	0	0.3	0	0.3
Capital + fixed cost	0.3	1.6	0.4	2.2

To capture any uncertainty in the cost impacts of refinery expansion, this study considered a few other refinery expansion options. Expansion of refinery alkylation capacity to process refinery propylene is possible but not likely in the HOF scenarios with declining gasoline demand. Most refiners without access to chemical markets for propylene are already doing this, while the remaining refiners will probably not see their incentives change due to increased HOF demand. Given its relatively high capital costs and low octane rating compared to C4 alkylation, C3 alkylation is more driven by high absolute gasoline prices in comparison to C3 olefins rather than severe octane constraints resulting from HOF fuel demand. Similarly, C5 alkylation units do not generate much—if any—octane for the HOF scenarios and still require significant capital investments. However, C5 alkylation in response to gasoline RVP reductions makes more sense than the response to octane generation.

Upgrading to CCR is also quite expensive. However, it is better for HOF octane requirements than are alkylation units. If a refiner is constrained on octane but still needs additional hydrogen to meet growing distillate demands, a CCR upgrade may be attractive because it offers these synergistic benefits; however, the gasoline pool will have a tendency to “heavy up,” and blending restrictions on DI and T90 are possible.

7. Conclusions

In this study, we conducted WTW GHG emission analysis of the production and use of 100-RON HOF gasoline. The analysis was done with detailed refinery LP modeling to producing HOF using E10, E25, and E40 ethanol blends; with different HOF market shares spanning from approximately 3 to 70% of total U.S. gasoline demand; and in the years 2022 and 2030. Regionally aggregated refinery LP models were developed for PADDs 1, 2, 3, 4, and 5 excluding CA and CA separately. We compared two scenarios of HOFV fuel economy gains relative to conventional vehicles: 5 and 10% gains in mpgge. We incorporated two key factors in the GREET model for WTW analysis: (1) refining energy intensities of gasoline components for HOF production with various ethanol blending options and HOF market shares and (2) two vehicle efficiency gains, 5% and 10%. The GHG emission results for HOFVs were compared with those of a baseline gasoline vehicle fueled with regular gasoline (87 AKI E10).

Most gasoline blends for HOF production are constrained by both octane and RVP. Production of 100-RON HOF with different ethanol blending levels changes the refinery BOB octane requirements. For example, due to the large octane increase required, E10 HOF production in the refinery industry is challenging. In addition to the required increase in gasoline BOB octane for HOF E10, refineries must produce BOB meeting RVP requirements in E10 versus E25 and E40. As ethanol blending level is increased, refineries can both produce less octane and face less RVP constraints. A consequence of increased ethanol blending with E25 and E40, coupled with decreased U.S. gasoline demand, is increased gasoline export.

Our LP modeling showed that U.S. refineries can produce the projected HOF demand in the 2022 and 2030 HOF scenarios with E25 and E40. The BOB RON required to produce E40 is lower than today's E10 gasoline, which essentially eliminates the need for new octane production capacity in refineries. The E25 scenarios, however, will require additional refinery octane production capacity, but the scale of the requirement is manageable, especially at low E25 HOF market shares. At higher shares of E25 HOF, however, the octane production becomes increasingly expensive. For additional octane production in the E25 HOF scenarios, changes in refineries could include higher reformer severity and throughput, less direct naphtha blending, FCC operational changes on naphtha and olefins for alkylation, and heavy FCC naphtha blending to gasoline (instead of diesel). Responses for the E40 HOF scenarios are nearly opposite to those of the E25 HOF scenarios. Isomerate blending tends to steadily decline in both scenarios—for E25 the decline is to control RVP and for E40 to reduce octane production. The isomerate pool is sensitive to many factors of refinery operation: the RVP, RON, and DI of a gasoline pool; product prices; HOF market shares; and ethanol blending levels, to name a few.

We see a stronger incentive for isomerate to provide a blending improvement in the E10 pools than in the E25 and E40 pools because of its low DI.

This study confirmed the general findings in the phase I study (Han et al. 2015) that the GHG emission impacts of introducing HOF are dominated by vehicle efficiency gains with the use of HOF and ethanol blending levels (as ethanol is estimated to have lower GHG emission intensities than gasoline), while the refining efficiency of gasoline BOB for various HOF market shares and ethanol blending levels (E10, E25, and E40) had only a small impact on WTW GHG emissions. The 5 and 10% mpgge fuel economy gains by HOFVs fueled by HOF helped reduce WTW GHG emissions by 4 and 8%, respectively, relative to baseline gasoline vehicles fueled by E10 regular gasoline. The additional WTW GHG emission reductions from corn ethanol blending to petroleum gasoline BOB were 4 and 9% for E25 and E40, respectively. As a result, when corn ethanol was used for blending and a 5% mpgge gain by HOFVs, total WTW GHG emission reductions from using E10, E25, and E40 HOFVs were 4–5, 9, and 13% lower, respectively, relative to baseline E10 vehicles. With an mpgge gain of 10% using E40 HOF, HOFVs achieved a total WTW GHG emission reduction of 17%. If corn stover ethanol was used for blending, additional WTW GHG emission reductions were achieved. As a result, if the corn stover ethanol was used, total WTW GHG emission reductions by HOFVs with E10, E25, and E40 were 8–9, 17, and 28%, respectively, relative to baseline E10 gasoline vehicles, with a 5% mpgge gain by HOFVs. 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 E10 regular gasoline. Also, this study showed that the WTW GHG emission reductions by E25 HOF relative to regular gasoline are fairly consistent throughout all regions.

A sensitivity analysis was performed with the E25 2030 MID scenario in PADDs 2 and 3 with respect to naphtha prices. With decreased naphtha prices, the HOF targets (49%) can be achieved with crude throughput decrease, naphtha production decrease, and/or naphtha diversion to gasoline export. The impacts of changed export gasoline and naphtha sales on the WTW GHG emissions of HOF BOB are less than 0.1 and 0.5 g CO_2e/MJ, respectively. The impact of crude type change was also investigated with the E25 2030 MID scenario in PADDs 2 and 3 using a 3-point change in API gravity coupled with a 0.4-percentage-point change in sulfur content. In both the Low and High API gravity scenarios, the HOF target productions (49%) were achieved. Due to the more severe upgrading, the Low API gravity scenario results in a high energy requirement. The impact of crude type on the WTW GHG emissions of HOF BOB by the 3-point change in API gravity coupled with 0.4-percentage-point change in sulfur content was estimated at about 1.0–1.4 g CO_2e/MJ.

For many refineries, producing high (50%) volumes of E10 HOF will be challenging. Higher E10 HOF volume can be produced with refinery additions such as fractionators, tankage, and piping, which will provide more blending flexibility by separating high-octane components from low-octane components for HOF production. To examine the impacts of these and other refinery expansion options, two configuration models (e.g., low- and high-octane refineries) were modeled in this analysis for E10 HOF scenarios, since E10 HOF production is highly constrained. Various process options were considered to boost the octane of gasoline components and produce as much HOF volume as possible. These options include reforming revamps, alkylation revamps, and isomerization addition. A high-octane refinery could produce 38% of total gasoline volume as HOF without any refinery expansion. With an OSBL improvement and alkylation upgrading, the high-octane refinery could produce more than 70% of total gasoline volume as HOF. On the other hand, with an OSBL improvement and isomerization unit addition, a low-octane refinery could increase the HOF production share from 0 to about 42% of the gasoline pool. This refinery expansion option could cost 1.6–2.2 cpg of gasoline, depending on financial assumptions to recover capital investments. Overall, the impact of the refinery expansion options on the WTW GHG emission of HOF BOB are not significant, ranging from 0.6 to 0.2 g CO_2e/MJ BOB between the low- and high-octane refineries, respectively. However, it is important to note that the small increases in the WTW GHG emissions of E10 HOF BOB with refinery expansions are valid under specific conditions and at limited HOF penetration. Thus, these results can neither be extrapolated to nor directly compared with the results from studies that assume higher HOF penetrations, such as Hirshfeld et al. (2014).

In summary, increasing the ethanol blending level from 10 to 25 and 40% enables refineries to meet a large demand of 100-RON HOF without refinery expansions. Moreover, HOFVs fueled with E25 and E40 HOF can produce large GHG emission reductions relative to baseline E10 vehicles fuels with regular E10 gasoline. The GHG emission reductions are largely due to the vehicle efficiency gains with the use of HOF and the increased blending level of ethanol with lower GHG intensities than gasoline. With the current level of ethanol blending at 10%, however, this study showed that the refineries would require a refinery expansion, such as an OSBL improvement for more selective blending, to meet a large demand of HOF at an aggregated level. Note that the reformer severity and throughput in the E10 HOF scenarios were significantly higher than those in the baseline and E25 and E40 HOF scenarios, which suggested substantial challenges to meet the increased octane demand by E10 HOF. Additionally, it should be noted that, while the refineries at an aggregated level can meet the demand, individual refineries could have different responses and challenges to the increased HOF demand. For example, our detailed investigation on refinery expansion options to increase the HOF production using two refinery configuration models (low- and-high octane refineries) showed that OSBL+ISOM could be a promising solution for allowing the low-octane refinery to produce a large volume of E10 HOF while the HOF share is still limited to 42% of total gasoline. Moreover, this study showed that DI is also an important fuel specification for E10 HOF in addition to RON and RVP, since HOF can become too heavy (or T50, T70 and T90 [the temperatures for the evaporated percentages of 50 percent, 70 percent and 90 percent, respectively] of HOF can be too high) with a high share of heavy reformate.

While both phases I and II of this HOF WTW analysis showed that ethanol is a very promising solution for a large increase in HOF production, this HOF WTW analysis does not rule out other blendstocks for HOF that can reduce GHG emissions and petroleum energy consumption significantly (e.g., biomass-derived reformates). Further analysis of producing HOF with other blendstocks would provide insight into refinery operation changes and WTW GHG emission impacts by these blendstocks. Furthermore, export of gasoline BOB and diesel was not limited but rather was used as an outlet of the residual streams in this model, without taking into account export market demands or prices, which led to a large discrepancy in diesel export between this model and EIA's AEO projection. Thus, a more rigorous assessment of the impacts of gasoline exports to examine more constraints on them, especially at high ethanol blending levels and large HOF market shares, is warranted. Additionally, this study was conducted under certain conditions. For example, HOF in this study is defined as 100 RON gasoline. However, E10 HOF with RON lower than 100 but higher than the current level (approximately 92 RON) could be considered to increase the volume of E10 HOF production while reducing vehicle efficiency gains. On the other hand, this study used the HOF market penetration from the HOF market adoption study by NREL, which is limited at 65% for E10 and E25 and 70% for E40. Thus, further analysis is needed to examine the impact of HOF at 100% penetration.

Lastly, this study did not take into account the indirect effect associated with reduced petroleum gasoline production. Wallington et al. (2016) showed that a large amount of biofuel production (e.g., ethanol for E25 and E40) could reduce crude oil demand and result in reduction of expensive and GHG-intensive oil sands production, lowering the GHG emissions intensity of petroleum products. This study, however, did not assume a significant reduction in crude oil demand even with a large share of E25 or E40 HOF, but increased the amount of export gasoline and assumed that the export gasoline market is large enough to absorb the additional export. To estimate the indirect effect, global crude market dynamics need to be modeled and investigated.

8. References

API (American Petroleum Institute), 2010. *Determination of the Potential Property Ranges of Mid-Level Ethanol Blends*. Washington, DC.

Andersen, V.F., J.E. Anderson, T.J. Wallington, S.A. Mueller, and O.J. Nielsen, 2010. "Vapor pressures of alcohol−gasoline blends." *Energy Fuels* 24, 3647–3654. doi:10.1021/ef100254w

Anderson, J.E., D.M. DiCicco, J.M. Ginder, U. Kramer, T.G. Leone, H.E. Raney-Pablo, and T.J. Wallington, 2012. "High octane number ethanol–gasoline blends: Quantifying the potential benefits in the United States." *Fuel* 97, 585–594. doi:10.1016/j.fuel.2012.03.017

Argonne National Laboratory, 2015. *GREET1 Model 2015*. http://greet.es.anl.gov/ (accessed 5.9.16).

ASTM (American Society for Testing and Materials International), 2013a. *Test Method for Research Octane Number of Spark-Ignition Engine Fuel*. Standard ASTM D2699-15a.

ASTM, 2013b. *Test Method for Motor Octane Number of Spark-Ignition Engine Fuel*. Standard ASTM D2700-16.

ASTM, 2015a. *Standard Test Method for Vapor Pressure of Petroleum Products (Mini Method)*. Standard ASTM D5191-15.

ASTM, 2015b. *Standard Test Method for Vapor Pressure of Petroleum Products (Reid Method)*. Standard ASTM D323-15a.

Brandt, A.R., T. Yeskoo, S. McNally, K. Vafi, H. Cai, and M.Q. Wang, 2015. *Energy Intensity and Greenhouse Gas Emissions from Crude Oil Production in the Bakken Formation: Input Data and Analysis Methods*. Argonne National Laboratory, Argonne, IL.

Burnham, A., J. Han, C.E. Clark, M. Wang, J.B. Dunn, and I. Palou-Rivera, 2011. "Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum." *Env. Sci. Technol.* 46, 619–627. doi:10.1021/es201942m

Cai, H., A.R. Brandt, S. Yeh, J.G. Englander, J. Han, A. Elgowainy, and M.Q. Wang, 2015. "Well-to-wheels greenhouse gas emissions of canadian oil sands products: implications for U.S. petroleum fuels." *Environ. Sci. Technol.* doi:10.1021/acs.est.5b01255

Canter, C.E., J.B. Dunn, J. Han, Z. Wang, and M. Wang, 2015. "Policy implications of allocation methods in the life cycle analysis of integrated corn and corn stover ethanol production." *BioEnergy Res.* 1–11. doi:10.1007/s12155-015-9664-4

CAPP (Canadian Association of Petroleum Producers), 2012. *2012 CAPP Crude Oil Forecast, Markets & Pipelines - Production and Supply Data*. http://www.capp.ca/library/publications/crudeOilAndOilSands/pages/pubInfo.aspx?DocId=209350 (accessed 1.4.13).

EIA (Energy Information Agency), 2014. *U.S. Energy Information Administration*. http://www.eia.gov/ (accessed 11.25.14).

EIA, 2015a. *Refinery Capacity Report 2014. U.S. Energy Information Administration*, Washington, D. C.

EIA, 2015b. *Annual Energy Review.* http://www.eia.gov/emeu/aer/contents.html (accessed 7.1.11).

EIA, 2015c. *Annual Energy Outlook 2015*. Report DOE/EIA-0383(2015). Washington, D.C.

EIA, 2015d. *International Energy Statistics.* http://www.eia.gov/countries/data.cfm (accessed 5.3.14).

Elgowainy, A., J. Han, H. Cai, M. Wang, G.S. Forman, and V.B. DiVita, 2014. "Energy efficiency and greenhouse gas emission intensity of petroleum products at U.S. refineries." *Environ. Sci. Technol*. 48, 7612–7624. doi:10.1021/es5010347

Englander, J.G., A.R. Brandt, A. Elgowainy, H. Cai, J. Han, S. Yeh, and M.Q. Wang, 2015. "Oil sands energy intensity assessment using facility-level data." *Energy Fuels*. doi:10.1021/acs.energyfuels.5b00175

EPA (Environmental Protection Agency), 2015a. *Control of Air Pollution from Motor Vehicles: Tier 3 Motor Vehicle Emission and Fuel Standards Final Rule - Regulatory Impact Analysis*. Report EPA-420-R-14-005. Washington, D.C.

EPA, 2015b. *Gasoline Reid Vapor Pressure*. https://www.epa.gov/gasoline-standards/gasoline-reid-vapor-pressure (accessed 5.4.16).

Ghandi, A., S. Yeh, A.R. Brandt, K. Vafi, H. Cai, M.Q. Wang, B.R. Scanlon, and R.C. Reedy, 2015. *Energy Intensity and Greenhouse Gas Emissions from Crude Oil Production in the Eagle Ford Region: Input Data and Analysis Methods*. Argonne National Laboratory, Argonne, IL.

Han, J., A. Elgowainy, M.Q. Wang, and V.B. DiVita, 2015. *Well-To-Wheels Greenhouse Gas Emissions Analysis of High Octane Fuels with Various Market Shares and Ethanol Blending Levels*, Report ANL/ESD-15/10. Argonne National Laboratory, Argonne, IL.

Hirshfeld, D.S., J.A. Kolb, J.E. Anderson, W. Studzinski, and J. Frusti, 2014. "Refining economics of U.S. gasoline: octane ratings and ethanol content." *Environ. Sci. Technol*. 48, 11064–11071. doi:10.1021/es5021668

Johnson, C., E. Newes, A. Brooker, R. McCormick, S. Peterson, P. Leiby, R.U. Martinez, G. Oladosu, and M.L. Brown, 2015. *High-Octane Mid-Level Ethanol Blend Market Assessment*. Report NREL/TP-5400-63698. National Renewable Energy Laboratory, Denver, CO.

Kalghatgi, G.T., 2001. "Fuel anti-knock quality - Part I. Engine studies." Technical Paper 2001-01–3584. SAE International, Warrendale, PA.

Leone, T.G., J.E. Anderson, R.S. Davis, A. Iqbal, R.A. Reese, M.H. Shelby, and W.M. Studzinski, 2015. "The effect of compression ratio, fuel octane rating, and ethanol content on spark-ignition engine efficiency." *Environ. Sci. Technol.* 49, 10778–10789. doi:10.1021/acs.est.5b01420

Moriarty, K., M. Kass, and T. Theiss, 2014. *Increasing Biofuel Deployment and Utilization through Development of Renewable Super Premium: Infrastructure Assessment*. Report NREL/TP-5400-61684. National Renewable Energy Laboratory, Denver, CO.

Mueller, S., and J. Kwik, 2013. *Corn Ethanol: Emerging Plant Energy and Environmental Technologies*. University of Illinois at Chicago, Chicago, IL.

ORNL (Oak Ridge National Laboratory), 2011. *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*. Oak Ridge, TN.

Qin, Z., C.E. Canter, J.B. Dunn, S. Mueller, H. Kwon, J. Han, M. Michelle, and M. Wang, 2015. *Incorporating Agricultural Management Practices into the Assessment of Soil Carbon Change and Life-Cycle Greenhouse Gas Emissions of Corn Stover Ethanol Production*. Report ANL/ESD-15/26. Argonne National Laboratory, Argonne, IL.

Qin, Z., J.B. Dunn, H. Kwon, S. Mueller, and M.M. Wander, 2016. "Influence of spatially dependent, modeled soil carbon emission factors on life-cycle greenhouse gas emissions of corn and cellulosic ethanol." *GCB Bioenergy* n/a-n/a. doi:10.1111/gcbb.12333

Renewable Fuels Association, 2016. *2016 Ethanol Industry Outlook*. Washington DC.

Schwaderlapp, M., P. Adomeit, A. Kolbeck, and M. Thewes, 2012. "Ethanol and its potential for downsized engine concepts." *Auto Tech Rev*. 1, 48–53. doi:10.1365/s40112-012-0022-z

Sluder, C.S., J.P. Szybist, R.L. McCormick, M.A. Ratcliff, and B.T. Zigler, 2016. "Exploring the relationship between octane sensitivity and heat-of-vaporization." *SAE Int. J. Fuels Lubr.* 9, 80–90. doi:10.4271/2016-01-0836

Speth, R.L., E.W. Chow, R. Malina, S.R.H. Barrett, J.B. Heywood, and W.H. Green, 2014. "Economic and environmental benefits of higher-octane gasoline." *Environ. Sci. Technol*. 48, 6561–6568. doi:10.1021/es405557p

Theiss, T.J., T. Alleman, A. Brooker, G. Chupka, A. Elgowainy, J. Han, S. Huff, C. Johnson, M. Kass, P. Leiby, R. Martinez, R. McCormick, K. Moriarty, E. Newes, G. Oladosu, J. Szybist, J. Thomas, M. Wang, B. West, 2016. *Summary of High-Octane Mid-Level Ethanol Blends Study.* Report ORNL/TM-2015/42. Oak Ridge National Laboratory, Oak Ridge, TN.

Thomas, J.F., B. West, and S.P. Huff, 2015. *Effects of High-Octane Ethanol Blends on Four Legacy Flex-Fuel Vehicles, and a Turbocharged GDI Vehicle.* Report ORNL/TM-2015/116. Oak Ridge National Laboratory, Oak Ridge, TN.

USDA (U.S. Department of Agriculture), 2014. *NASS-National Agricultural Statistics Service.* http://www.nass.usda.gov/index.asp (accessed 7.1.14).

Wallington, T.J., J.E. Anderson, R.D. De Kleine, H.C. Kim, H. Maas, A.R. Brandt, and G.A. Keoleian, 2016. “When comparing alternative fuel-vehicle systems, life cycle assessment studies should consider trends in oil production.” *J. Industrial Ecology*. doi:10.1111/jiec.12418

Wang, M., J. Han, J.B. Dunn, H. Cai, and A. Elgowainy, 2012. "Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for U.S. use." *Environ. Res. Lett*. 7, 45905. doi:10.1088/1748-9326/7/4/045905

Wang, Z., J.B. Dunn, J. Han, and M.Q. Wang, 2015. "Influence of corn oil recovery on life-cycle greenhouse gas emissions of corn ethanol and corn oil biodiesel." *Biotechnol. Biofuels* 8, 178. doi:10.1186/s13068-015-0350-8

Yeh, S., A. Zhao, and S. Hogan, 2014. *Spatial and Temporal Analysis of Land Use Disturbance and Greenhouse Gas Emissions from Canadian Oil Sands Production*. Institute of Transportation Studies, University of California, Davis, CA.

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