Well-to-Wheels Energy and Greenhouse Gas Emission Analysis of Bio-Blended High-Octane Fuels for High-Efficiency Engines

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Abbreviations

AEO	Annual Energy Outlook
AKI	Anti-knock index
APR	Aqueous-phase reforming
ASTM	American Society for Testing and Materials
BOB or gasoline BOB	Blendstock for Oxygenate Blending, the fossil hydrocarbon gasoline produced in refineries, to be blended with bio-content
BAU gasoline	Today's business-as-usual E10 gasoline, including four gasoline types including conventional regular gasoline, conventional premium gasoline, reformulated regular gasoline, and reformulated premium gasoline
BR set	Bioreformate (BR) blended gasoline fuels (finished gasolines), blending BR gasoline BOBs with bio-reformate. Although bio-reformate is not an oxygenate, the term "BOB" is used for consistency
CA	California
CARB	California Air Resources Board
CG	Conventional gasoline
CGM	Corn Gluten Meal
COKHCK	Coking hydrocracking
CRK	Cracking configuration
CRC	Coordinating Research Council
DGS	Distiller' Grains with Solubles
DI	Drivability index
E set	Bio-ethanol blended gasoline fuels, blending BOB gasoline and bio-ethanol
EPA	U. S. Environmental Protection Agency
Export gasoline	The excessive gasoline BOB produced in refineries for export and it does not contain ethanol. In the present study, the exported gasoline is assumed to meet regulation in Mexico
EtOH	Ethanol
FCC	Fluidized catalytic cracking
Finished gasoline or gasoline fuels or finished gasoline pool	The blended gasoline fuels (mixtures of many refinery BOB streams and bio-blendstock), which are subject to meet ASTM regulations and suitable to be used for vehicle operations. In the present study, they apply to the blended E set and BR set gasoline fuels
G/D	Gasoline/diesel volumetric ratio
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
HOF gasoline	High octane fuels; pool of two gasoline types, specifically HOF CG and HOF RFG
HvyCOK	Heavy coking (configuration)

LCA	Life-cycle analysis
LtCOK	Light coking (configuration)
MON	Motor octane number
MY	Model year
NC4	Normal butane
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
OS	Octane sensitivity
PADD	Petroleum Administration Defense District
PTW	Pump-to-wheel
RFG	Reformulated gasoline
RON	Research octane number
RVP	Reid vapor pressure
SMR	Steam methane reforming
T&D	Transportation and distribution
TLO	Tight light oil
WG set	Wood-derived gasoline blended fuels
WTP	Well-to-pump
WTW	Well-to-wheels

Preface

Fuels used in light-duty vehicle transportation have undergone a diversification in the United States over the past few decades. These fuels include liquid and gaseous fuels and electricity, which are derived from solid, liquid, gaseous, and renewable energy sources. The search for relevant and appropriate transportation fuels has been driven by economic, national security, and environmental concerns. Fuel economy improvements can lead to significant annual fuel cost savings for Americans,[1] and producing fuels from domestic resources has the potential to increase U.S. jobs, support rural economies, reduce tailpipe carbon dioxide (CO_2) emissions, and, by keeping energy financial resources in the United States, add to U.S. energy security and resiliency. The three reports U.S.DRIVE is publishing in 2018 on behalf of its Fuels Working Group (FWG) are focused on an assessment of the potential of a range of higher octane conventional and renewable fuels to enable increased light-duty vehicle efficiency and reduced well-to-wheels (WTW) greenhouse gas (GHG) emissions, and their potential impact on fueling infrastructure.

Liquid fuels continue to hold significant potential in light-duty vehicle transportation for several reasons: (1) liquid fuels have high energy density; (2) energy companies know how to make liquid fuels on the billion-gallon annual scale efficiently; (3) there exists a ready means to transport and dispense such fuels; and, (4) transitioning the market of vehicles to a new or modified fuel is simplified if it is a liquid. Auto manufacturers are interested in knowing in advance what fuels are likely to be developed and deployed successfully because it can take from 5 to over 10 years to design, develop, and bring to market. Additionally, considering the large current vehicle population and vehicle lifetimes of 15 to 20 years, these factors confirm that conventional engine technologies will continue to comprise a significant portion, if not the majority, of the nation's light-duty vehicle fleet for the next several decades.

Varying fuel composition to increase the octane rating of fuel for spark-ignition engines (e.g., gasoline) is widely recognized as a potential means to address economic, national security, and environmental concerns associated with transportation energy. Such fuels can enable higher fuel economy and achieve associated reductions in carbon emissions from vehicles. For example, blending with low-carbon biofuels, some of which have inherently high octane ratings, can increase the finished fuel octane ratings and reduce its environmental impact.[2] Producing fuels with elevated octane ratings through the modification of fuel composition, however, may have the unintended consequence of increasing energy use and associated emissions from fuel production, due, for example, to both the conversion of biomass to biofuels and/or the production of different base gasoline blend stocks.

U.S.DRIVE, a government-industry consortium that includes the U.S. Department of Energy, energy companies (including utilities), and auto manufacturers, works in 16 technical areas collaborating to find new solutions to pre-competitive research questions regarding new energy sources, efficiency, and emissions. In the arena of future fuels, U.S.DRIVE Partners' expressed an interest to learn more about potential new high-octane liquid fuels for conventional and hybrid vehicles. Energy companies are interested in ensuring customers have access to fuels with which to operate their vehicles, and auto manufacturers are interested in ensuring the public can purchase vehicles that meet both government

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1. Greene, D., and J. Welch. 2017. The impact of increased fuel economy for light-duty vehicles on the distribution of income in the U.S.: A retrospective and prospective analysis. Knoxville, TN: Howard Baker Center for Public Policy. Online at http://bakercenter.utk.edu/white-paper-onthe-impact-of-increased-fuel-economy-for-light-duty-vehicles, accessed June 21, 2017.
2. Han, J. et al. 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.

vehicle fuel economy requirements and customer desires. Therefore, U.S.DRIVE is interested in learning whether, if a vehicle and engine were designed as a system, a more optimal fuel that addresses economic, national security, and environmental concerns could be realized.

Toward these ends, U.S.DRIVE formed the FWG, to study fuel effects on combustion, and the FWG evaluated several fuel and engine combinations to determine if there are more optimal fuel/engine combinations that could be designed and deployed in the future. In the broadest perspective, the research compares various high octane number fuels in the context of engine performance and their relative life-cycle carbon impacts, as well as potential impacts on fueling infrastructure and associated costs. The FWG specifically examined three areas: (1) how these fuels might function in conventional spark-ignition engines under a variety of operating conditions; (2) what the life-cycle impact on efficiency and environmental metrics, including GHG emissions, for such fuels might be; and (3) how these fuels fit within the existing U.S. fuel refinery and transport infrastructure.

With regard to the first area of research, the FWG built on an existing Coordinating Research Council (CRC) study, AVFL-20, that explored the potential vehicle energy use, volumetric fuel economy, and tailpipe CO_2 emissions effects of different research octane ratings (research octane number, RON), octane sensitivity (OS), and ethanol content in gasoline.[3] Because there are potential non-ethanol biofuel pathways to increased octane that were not included in the scope of AVFL-20, the FWG set about to address these gaps by expanding on the AVFL-20 project to include fuels with non-ethanol bio-derived feedstocks.

In the second area of research, the FWG examined life-cycle impacts, specifically the changes in tailpipe CO_2 emissions in relation to changes in fossil CO_2 emissions from fuel production (both petroleum and renewable biofuels). The FWG understood that because production of gasoline with increased octane ratings together with production of renewable biofuels at the national scale may require additional energy input, it is important to consider this energy requirement in combination with potential energy savings enabled in the light-duty vehicle engines that automakers produce. Conducting a life-cycle analysis (LCA), or WTW assessment, for each of the potential pathways towards a high-octane fuel is an effective means of estimating the energy consumption and GHG emissions impacts for each pathway. Completing an LCA for each fuel blend examined in the engine studies report uses estimates of vehicle energy efficiency for typical driving patterns and potential energy production requirements for each fuel blend.

In the third area of research, the FWG identified other important considerations in assessing the potential of a fuel blend to a succeed in the marketplace. Specifically, the FWG is interested in understanding the compatibility of potential high-octane biofuel formulations with the existing refinery, transport, and fueling infrastructure. Developing a fuel that requires an entirely new fueling and fuel transport infrastructure is clearly an obstacle.

The following report addresses life-cycle impacts of the fuels studied, and while it stands alone for its method, results, and conclusions and so may be viewed independently, it is best read, considered,

[3] Sluder, et al., Report # AVFL-20, Coordinating Research Council, November 2017. https://crcao.org/reports/recentstudies2017/AVFL-20/AVFL20_Final%20Report_11032017.pdf.

and understood in association with the companion reports entitled *U.S.DRIVE Fuels Working Group Engine and Vehicle Modeling Study to Support Life-Cycle Analysis of High-Octane Fuels*,[4] and *Potential Impacts of Increased Ethanol Blend-Level in Gasoline on Distribution and Retail Infrastructure*.[5] As such, this report is part of a larger coordinated effort by the U.S.DRIVE Partnership.

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[4] Sluder, C.S., D.E. Smith, J.E. Anderson, T.G. Leone, and M.H. Shelby. 2019. *U.S. DRIVE Fuels Working Group Engine and Vehicle Modeling Study to Support Life-Cycle Analysis of High-Octane Fuels*. Prepared by Oak Ridge National Laboratory and Ford Motor Co. https://www.energy.gov/eere/vehicles/downloads/us-drive-fuels-working-group-high-octane-reports.

[5] Monroe, R., Kass, M. and McConnell, S. 2019. *Potential Impacts of Increased Ethanol Blend-Level in Gasoline on Distribution and Retail Infrastructure*. Prepared by General Motors Company, Oak Ridge National Laboratory and Marathon Petroleum Company. https://www.energy.gov/eere/vehicles/downloads/us-drive-fuels-working-group-high-octane-reports.

Executive Summary

The Study

A well-to-wheels (WTW) analysis has been carried out by Argonne National Laboratory for the Fuels Working Group (FWG) of U.S.DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability), a partnership between the U.S. government and automotive and energy industries, to examine the energy and greenhouse gas (GHG) effects of producing fuels with higher octane numbers and their combustion in advanced engines. The fuels evaluated in this WTW study were formulated with various gasoline blendstock and renewable blending components and tested by U.S.DRIVE and Coordinating Research Council (CRC) members in a turbocharged gasoline direct injection (GDI) engine at several compression ratios. Our analysis examines the potential benefits of reducing energy use and GHG emissions throughout the WTW cycle by considering both the energy and emissions of production of these higher octane number fuels and their use in engines, with fuel efficiency improvement enabled by high octane number fuels with low-carbon renewable contents. The combination of higher engine efficiency and low-carbon bio-blended fuels can reduce fossil energy use and GHG emissions during the vehicle operation stage, which has the majority of energy use and GHG emissions of the WTW cycle.

The Fuels Modeled

Three sets of bio-blended fuels were investigated in this study: E set fuels (ethanol blended fuels), WG set fuels (woody biomass-derived blended fuels), and BR set fuels (bioreformate blended fuels). The E set fuels are ethanol blended with petroleum refinery blendstocks with a range of research octane numbers (RON) of 91-101, octane sensitivity (RON-MON) of 6–12, and blending levels of 10% ethanol (E10), 20% ethanol (E20), and 30% ethanol (E30), all on volumetric basis. All but one of the formulations were research fuels developed and tested in the CRC Advanced Vehicle/Fuel/Lubricants Committee (AVFL)-20 program. In the WTW study, two sources or feedstocks for ethanol production were evaluated: corn starch and corn stover. The WG set fuels were produced via blending petroleum refinery streams with woody biomass derived streams at 9 vol% and 27 vol%. The woody bio-stream was produced via woody biomass gasification followed by methanol/dimethyl ether (MeOH)/DME conversion to gasoline range hydrocarbons. The wood-derived bio-blendstockwas considered a woody bio–gasoline developed by an integrated biorefinery using Carbona gasification and Topsoe TiGAS processes, under DOE award No. DE-EE0002874. The BR set fuels contain an aromatic hydrocarbon mixture blendstock as a surrogate for bioreformate, which is a cellulosic bio-blendstock developed through an essential catalytic conversion step—aqueous-phase reforming (APR). The resultant bioreformate, is highly aromatic with high RON, and its properties are similar to those of refinery reformate. The BR set fuels have 9 vol% and 27 vol% bioreformate content. The key features of these three sets of fuels are shown in Figure ES-1.

The bio-components—ethanol, WG stream and BR stream—are chemically distinct with widely differing chemical composition and properties such as Reid vapor pressure (RVP) [1], RON, distillation temperatures, and aromatic content. These differences require various refinery operation adjustments to produce petroleum blending streams—blendstocks for oxygenate blending (BOB)—that will enable the finished blended product to meet regulated fuel specifications. Note that for convenience, throughout the report we refer to these refinery produced blendstocks as BOBs, despite the fact that no oxygenates are contained in the WG and BR components.

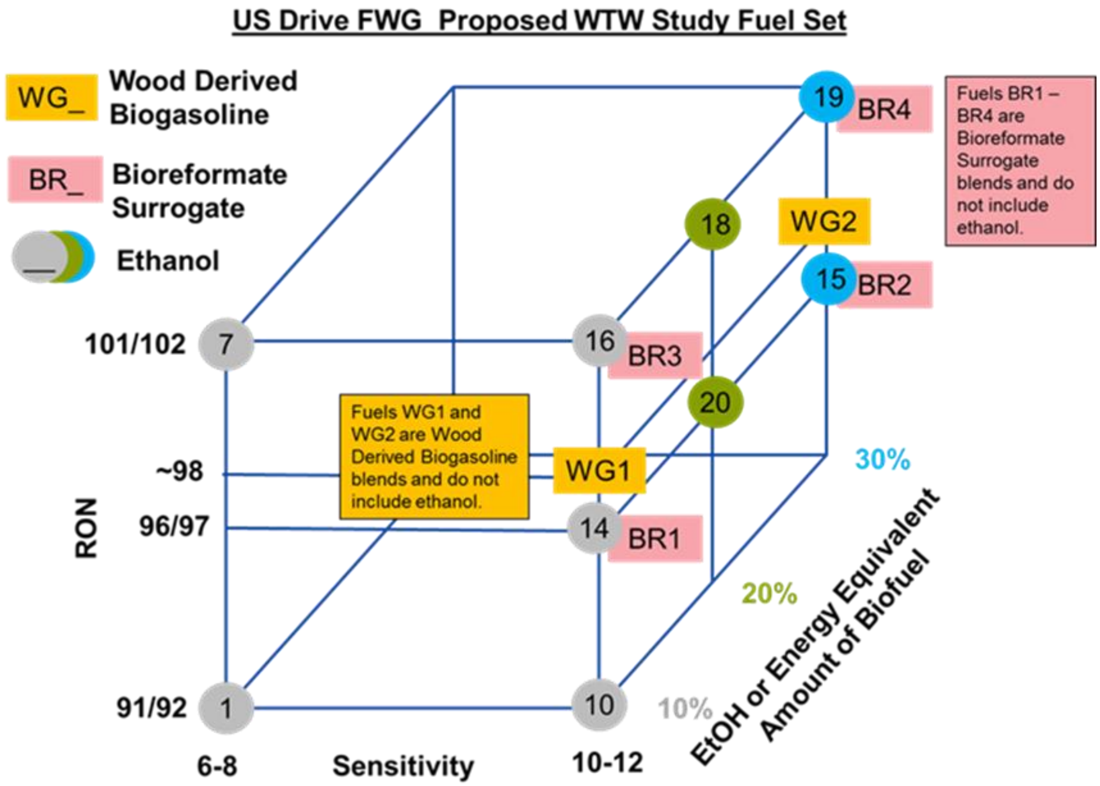


Figure ES-1. Key Features of the Gasoline Fuels in This Study

Fuel Production Modeling

The petroleum refinery operation adjustments (in response to produce the specific BOBs to blend with various bio-blendstocks) cause variations in the refinery mass balance and energy balance and, in turn, variations in refinery stage GHG emissions. It is worth mentioning that the bio-blendstocks are not produced but are only blended with BOBs in refineries, thus the energy uses and GHGs required to their production are calculated separately, independent of refinery operations. Understanding the changes to petroleum refining activities needed to produce such fuels is key to investigate the potential GHG emission reduction benefits of implementing these high-octane (for higher fuel economy) bio-blended fuels (for biogenic CO_2 emission). Linear programming (LP) modeling is an appropriate technique for simulating these activities. Various LP modeling analyses were designed, constructed and conducted by Jacobs Consultancy with its proprietary refinery modeling system in Haverly's GRTMPS LP operating platform.

Using LP modeling, we investigated refinery responses mainly in Petroleum Administration Defense District (PADD) 3 (for all fuels in the present study), in California (CA) (for E set fuels), and, in some cases, in PADD 2 (for BR set fuels only). The models included both an aggregated notional refinery model and specific process configuration models. The timeframes of the study were 2022 and 2040 with model key input information, such as projected crude slate, American Petroleum Institute (API) crude gravity, crude price, gasoline and diesel demand, and product slate extracted from the U.S. Energy Information Administration (EIA) Annual Energy Outlook 2016 (AEO2016) [2], California Energy Commission (CEC) [3], and other sources cited later in report. For 2022 cases, the bio-blended high octane fuels (HOF) were assumed to have 50% market penetration of the U.S. gasoline market, with the rest being “business-as-usual” (BAU) E10 gasoline pool. For 2040 cases, the bio-blended fuels were assumed to have 100% market penetration, completely replacing the currently available gasoline of all types. The assumption was made that production of these biofuels on commercial scale is feasible. Thus, no constraints were assumed for the production of the increased volumes of ethanol, bioreformate, or wood-derived gasoline.

LP modeling of production of the E set, WG set, and BR set fuels in various regions and refinery configurations show that feasible solutions cannot be achieved for some cases (denoted as infeasible), thus revealing the inherent challenges of producing high-octane fuels to meet all incumbent specifications and projected demands. In particular, none of the WG modeling cases yielded feasible solutions owing to the unfavorable properties of the WG blending components (high vapor pressure and low octane). Thus, this report focuses on the analysis of E set fuels and BR set fuels with feasible solutions from LP modeling.

For the feasible cases, the simulated petroleum refinery results from Jacobs Consultancy’s LP modeling were processed and incorporated into the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET®) model for WTW analysis. The GREET model has been developed by Argonne National Laboratory since the 1990s and is updated annually. It tracks the energy consumption, GHG emissions and other pollutants, and water consumption associated with transportation fuels production and use.

The GREET 2016 version serves as the essential platform on which we implemented the WTW analysis of these bio-blended, higher octane gasoline fuels. The key stages of the fuel pathways, up to refueling station pumps, are shown in Figure ES-2 below. Most key well-to-pump (WTP) stages have been established in GREET. For this study, energy and mass balances were updated or modified for some of the WTP stages to adapt to the specific simulations conducted here.

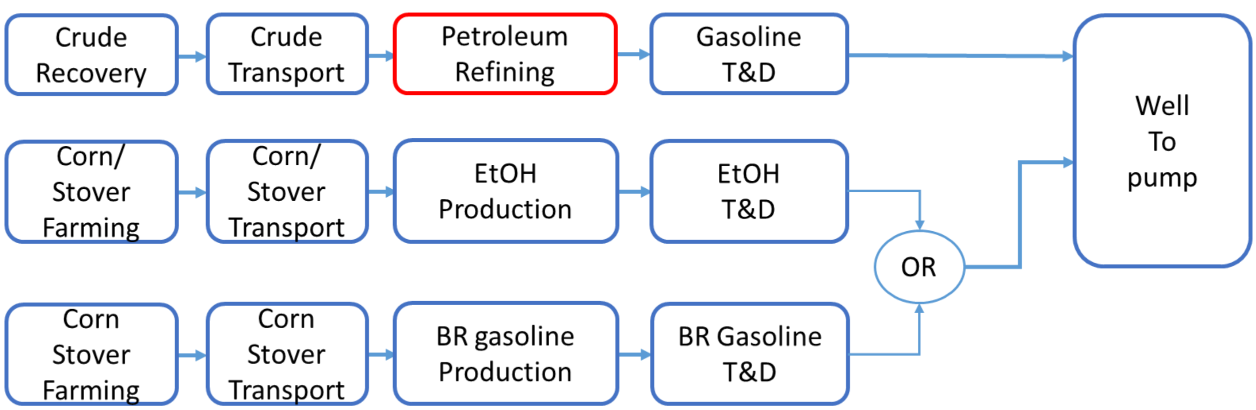


Figure ES-2. Key Stages of Well-to-Pump Analysis of Bio-Blended Fuels

Vehicle Operation Modeling

For the pump-to-wheel (PTW) stage, energy consumption and GHG emissions of vehicle operation were provided by Oak Ridge National Laboratory (ORNL). In the engine testing and vehicle simulation study of this U.S.DRIVE FWG effort, an engine study was performed by ORNL examining the potential benefits of using gasoline with increased octane numbers and an engine using increased compression ratios to deliver higher efficiency. The fuel economy gains of improvements in engine efficiency enabled by high-octane fuels were projected via Autonomie modeling by ORNL, and are based on engine test data augmented by supplementary calculations and literature information. The details are documented in the 2018 U.S.DRIVE report by Sluder et al. [4]. Simulated fuel economy results based on three engine efficiency gain assumptions were used in GREET for the WTW analysis.

Conclusions

This study has the following main conclusions.

- Relative to baselines (the WTW GHG emissions of domestic E10 gasolines produced in base cases), reductions in WTW GHG emissions were obtained for the E set (ethanol blended gasolines) (up to 20%) and BR set (bioreformate blended gasolines) cases (up to 22%). In general, WTW GHG emission reductions are proportional to the amount of bio-blending components.

- For a future fleet fueled by high-octane bio-blended gasolines, the greatest contribution to the WTW GHG reductions is attributed to the WTW GHG reductions of biofuel blending components relative to the petroleum BOBs.

The vehicle fuel economy gains enabled by higher RON fuels also contribute to lower WTW GHG emissions.

- Many LP modeling cases did not yield feasible solutions, reflecting the challenges refineries encounter in producing BOBs for some of the high-octane fuels. For the feasible cases, the impact of changes to refinery operations on energy use and GHG emissions is a lesser factor compared with the biofuel blending effects and higher RON enabled fuel economy gain.

- Refinery configuration differences (along with their different crude slates) have a more pronounced effect on refinery GHG emissions than the impact of gasoline properties such as RON and the level of bio-components for the fuels considered. For one set of bio-blended BOBs produced in different refineries, the difference in GHG emissions is about 5-12 g/MJ gasoline BOB. On the other hand, for a given refinery to produce various BOBs, the differences in GHG emissions were about 1–2 g/MJ.

- Regionally, the energy use and GHG emissions in the modeled aggregate refineries increase from PADD 3 to California (CA) and again to PADD 2 during crude recovery (crude oil production and transportation), and from PADD 2 to PADD 3 and again to CA during refinery operations.

- For E set fuels with 10% and 20% ethanol, their domestic gasoline BOBs have higher WTP GHG emissions than baselines. In contrast, for E30 gasolines, Fuel 15 and Fuel 19, their domestic gasoline BOBs have lower WTP GHG emissions than baselines. This is because the 30% ethanol blending provides significant octane number boost to the gasoline pool, thus reducing a refinery's need for increasing the octane numbers of the BOBs.

- For BR set fuels, many BOBs have lower WTP GHG emissions than baselines (the base case E10 gasoline BOB), owing to the high octane of the BR blendstock, which eases refinery pressure to boost octane numbers for BOBs. For a few cases, the BOB

WTP GHG emissions are slightly higher than those of baselines, responsive to refinery operational changes specific to each fuel production.

- For each set of gasoline BOB produced in the configuration refinery, energy use and GHG emissions increase in the order of cracking (CRK) to light coking (LtCOK) to coking hydrocracking (COKHCK) and to heavy coking (HvyCOK) configuration, primarily due to differences in hydrogen demand and its production via steam methane reforming (SMR).

- The production of bioreformate requires a significant amount of hydrogen. When hydrogen is from a fossil source (purchased H_2 from natural gas via SMR), the WTP GHG emissions of BR set fuels (the sum of gasoline BOB GHG emission and bioreformate GHG emissions) are much higher than that of baselines (base case E10 production).

- The PTW stage has lower GHG emissions for HOF fuels, compared with baseline fuels, because of the bio-blendstock content (which releases biogenic GHG via combustion) and the vehicle efficiency gain enabled by these fuels (for per-mile basis). In the present study, the GHG reductions in the PTW stage are greater than the GHG emissions increases for BOBs in the WTP stage

- The WTW GHG emissions of the E set fuels and BR set fuels with high octane (RON of 96 and 101) are lower than those of baseline (BAU) in both 2022 and 2040, regardless of the refinery configurations, ethanol sources, or hydrogen sources for BR production. This is primarily due to the higher biofuel content and secondarily to greater engine efficiency.

- Generally, compared with the baselines (domestic gasolines produced in base cases), the E set and BR set domestic fuels produced in 2040 have greater WTW GHG emission reductions than those produced in 2022, for both per MJ and per mile basis. The assumed HOF's market share increases from 50% to 100% over these years, which leads to a higher bio-blend share in the total gasoline pool, less fossil energy use, and more engine efficiency gain owing to the high octane of HOF.

- The WTW total energy use for each E set or BR set fuel can vary significantly, depending on such factors as bio-blend source/production pathway, crude slate, PADD, and refinery configuration. For the WTW fossil energy use, natural gas (and to a lesser extent ,coal) plays an important role in addition to petroleum energy. Along the WTW pathways, the energy ratio of (natural gas plus coal)/petroleum (MJ/MJ) can range from 15% to 62%.

Key results are shown in Figures ES-3 and ES-4.

In Figure ES-3, the six bars reflect a combination of the two ethanol feedstocks and three fuel economy gains (derived from different octane number/compression ratios [ON/CRs]).

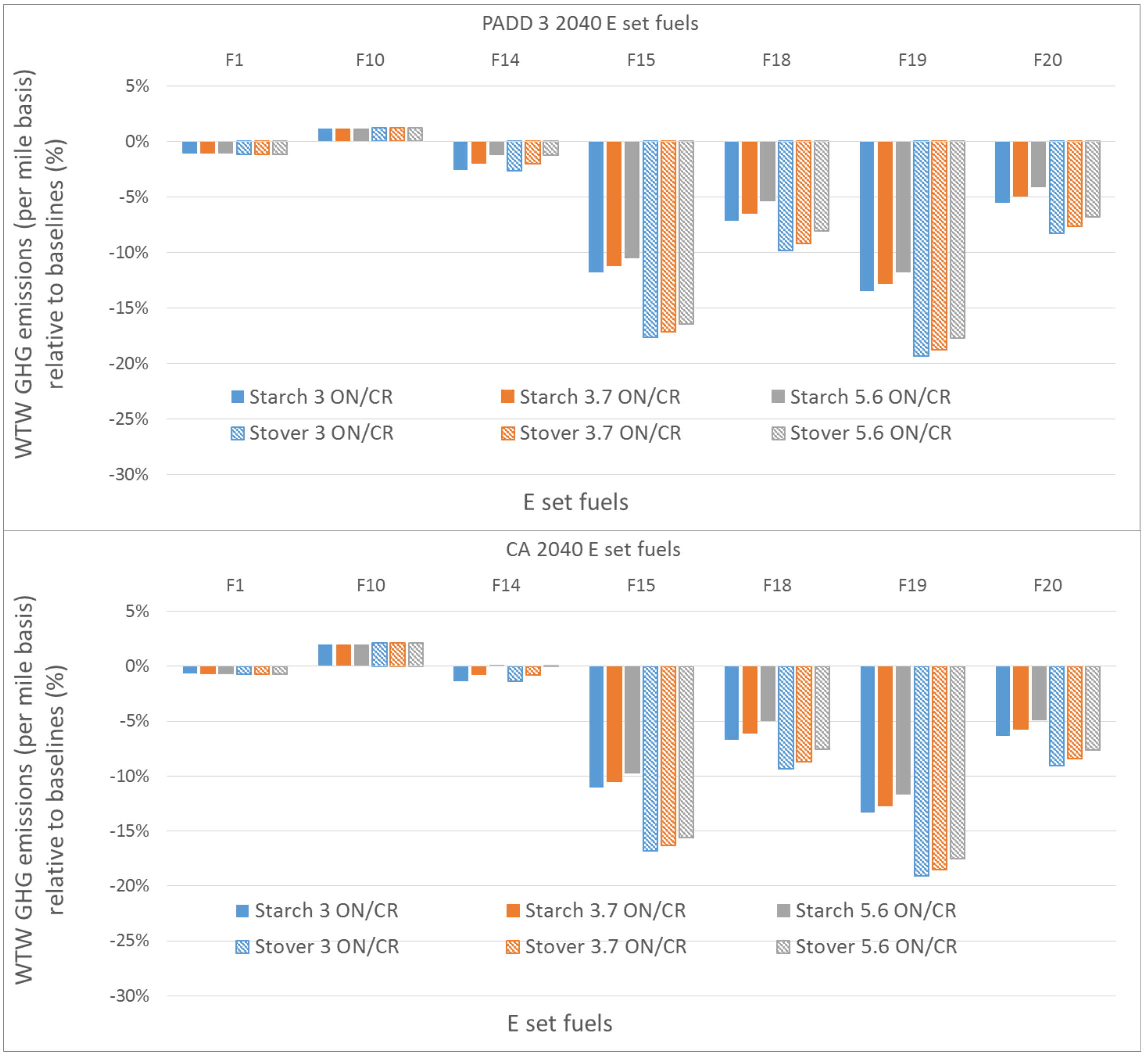


Figure ES-3. Projected WTW GHG Emission Changes Relative to Baseline (current E10 AKI[6] of 87) for E Set Fuels Produced in PADD 3 and CA Refineries in 2040. Dual Sets of Baselines Used with Ethanol from Corn Starch and Corn Stover, Respectively.

The figure shows projected results of WTW GHG emissions of E set fuels produced in PADD 3 and in CA relative to baselines on a per-mile basis in 2040. The 2040 results include those with ethanol from both corn starch and corn stover. As expected, the E set fuels with corn stover ethanol have greater GHG reduction benefit than with corn starch ethanol. Relative to baselines in each region (current E10 with anti-knock index (AKI) 87), the E set fuels produced in PADD 3 has greater reductions of GHG emissions than those in CA, for both corn starch ethanol and corn stover ethanol. In each region, E set fuels with the same ethanol source as baselines (corn starch ethanol or corn stover ethanol) show sizeable GHG emissions reduction with 30% ethanol blending (F15 and F19). In particular, F19 shows the greatest GHG emission reductions owing to its high RON of 101.The different ON/CR value assumptions have a small impact on GHG emissions reduction, about 1%–2%.

[6] Anti knock index

Figure ES-4 shows the projected GHG emissions of BR set gasolines produced in PADD 2 and PADD 3 relative to those of baselines in 2040, with three hydrogen sources for bioreformate production. In 2040, all BR set gasoline is assumed to be HOF gasoline with bioreformate blending, and thus does not contain any ethanol content. However, in 2040, baseline E10 with corn starch ethanol and corn stover ethanol are assumed for comparison, resulting in two sets of comparison results regarding ethanol sources. All the BR set gasolines show greater GHG reductions relative to baselines with corn starch ethanol than with corn stover ethanol. This is because the latter has lower GHG emissions than the former.

The BR set gasolines with (biomass) gasification hydrogen shows greatest GHG emissions. The cases with in-situ hydrogen source (in BR plants) lead to slightly less GHG reduction benefits than the cases with gasification hydrogen, while the cases with purchased hydrogen (with natural gas SMR) show the least GHG emissions benefits. The BR set fuels produced in PADD 3 show slightly greater GHG emission reductions than in PADD 2. With high RON of 101, BR4-T shows higher GHG emission reductions than BR 2 does. Again, the different ON/CR assumptions have a small (about 1%–2%) impact on GHG emission reductions.

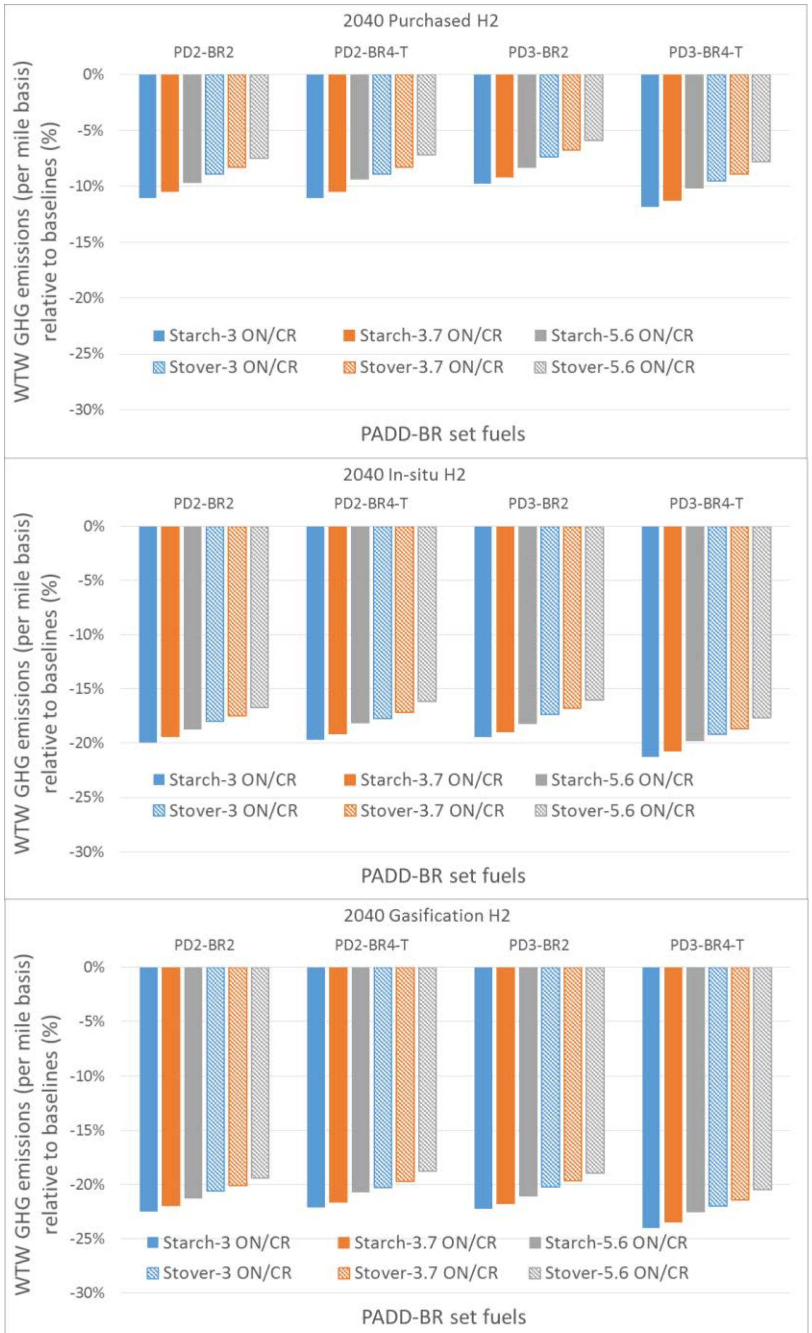


Figure ES-4. Projected GHG Emissions Changes of BR Set Fuels (no ethanol) Relative to Baseline (current E10 87 AKI) Produced in PADD 2 and PADD 3 Refineries in 2040. Results are for hydrogen from three sources: Purchased H_2, In-situ H_2, and Gasification H_2. Dual Sets of Baselines Used with Ethanol from Corn Starch and Corn Stover, Respectively.

Purchased H_2: from industrial hydrogen supplied via Steam Methane Reforming using fossil natural gas.
In-situ H_2: on site produced from hydrolysate reforming, hydrolysate is bio-intermediate product during bioreformate production.
Gasification H_2: produced via gasification of woody biomass feedstock which is purchased for hydrogen production specifically, in addition to the purchase of corn stover as feedstock for bioreformate production.
T refers to toluene that is used as a surrogate for bioreformate.

1. Introduction

Driven by both global efforts and domestic regulations to curb greenhouse gas (GHG) emissions and reduce energy consumption, automakers, energy companies, and government agencies are making concerted efforts to identify and to produce appropriate transportation fuels to power vehicles more efficiently and reduce fossil energy use, GHG emissions and other air pollutant emissions. Two common approaches include improving engine efficiency via the improvement of gasoline fuel anti-knock properties (increase octane numbers), and blending renewable or low-carbon fuel components into petroleum fuels. Combining these two approaches, this study aims to conduct a well-to-wheels (WTW) analysis on the GHG emissions and energy consumption of producing and consuming high octane bio-blended gasoline fuels for vehicles with spark-ignited engines. The WTW analysis includes the major stages of crude oil recovery/transportation, crude oil refining, biomass farming/transportation, biofuel production, and gasoline combustion in vehicles.

On the fuel side, blending petroleum fuels with low-carbon biofuels can significantly reduce the carbon footprint of finished fuels [5]. As some biofuels have inherently high octane numbers, there may be synergy by producing high-octane gasoline fuels with low-carbon biofuels to reduce GHG emissions.

However, the energy use and GHG emissions of converting biomass to biofuels need to be taken into account. Further, the distinctive features of various bio-blend streams and different blending levels [6] require the production of different base gasoline blendstocks in refineries to enable the final blended gasoline to meet fuel specifications. Thus, the energy use and GHG emissions associated with refinery operational changes also need to be taken into account. For convenience, in this report the base gasoline blendstocks are referred to as “BOBs” (blendstocks for oxygenate blending) despite the fact that some of the bio-components considered in this study are not oxygenates. The operational changes made in refineries to meet finished gasoline fuel requirements may change the energy use and GHG emissions of the gasoline products.

On the other end of the fuel lifecycle, vehicle operation is the major stage for GHG emissions, accounting for about 80% of total WTW GHG emissions for light-duty vehicles with spark ignition engines. Therefore, any efficiency gains in vehicle operation would lead to a notable impact on GHG emissions. High octane gasoline fuels for these vehicles can enable higher compression ratio to be used, improving engine efficiency, and thus reducing vehicle fuel consumption. For example, Leone et al. showed that raising the engine compression ratio from 10:1 to 12:1 can enable an engine efficiency gain of 5%–7%, and further raising the ratio to 13:1 can enable an efficiency gain of 6%–9% [7]. However, achieving the compression ratio increase requires a commensurate increase in research octane number (RON) with 2–9 RON increases for each compression ratio increase, depending on cylinder displacement, geometry, and engine technology [7][8].

Estimating the net change in GHG emissions associated with the use of high octane bio-blended fuels for vehicle operation with enhanced engine efficiency requires a lifecycle analysis (LCA), or WTW analysis, of fuels and vehicles. The WTW analysis in this study uses the GHGs, Regulated Emissions, and Energy use in Transportation (GREET®) model. The GREET model has been developed by Argonne National Laboratory since the 1990s and includes more than 100 transportation fuel production pathways. This study uses the GREET model to estimate GHG emissions and energy use for all the stages of fuels production and utilization, with new refinery operation information incorporated to reflect impacts of high octane fuels (HOFs) to refinery emissions and vehicle efficiency. A distinguishing feature of this study is the use of two key data sources. First, for the petroleum refinery stage, the energy and mass balance is simulated from extensive linear programming (LP) modeling of refinery operations, Second, for the vehicle operation stage, engine efficiency gain was studied in a separate, detailed study and used to estimate vehicle fuel economy with the Autonomie model.

This study includes three sets of bio-blended gasoline fuels, which were blended and tested in the engine testing and vehicle simulation study for U.S.DRIVE and from a prior Coordinating Research Council (CRC) study (AVFL-20) [9], and include bio-ethanol blended fuels (E set), woody biogasoline (WG set), and bio-reformate surrogate (BR set) blended gasoline. These three sets of fuels include bio-blendstocks produced from various biomass sources, with different bio-blend levels, RON and gasoline fuel octane sensitivity (RON-MON, where MON refers to the motor octane number).

- **E set fuels:** nine ethanol-containing fuels were studied with ethanol blending levels ranging from 10 to 30 vol%, RON ranging from 91 to 101, and octane sensitivity from 6 to 12. For current commercial gasoline fuels in the US, most contain 10% ethanol derived from corn starch, and the remaining volume from refined petroleum blendstock for oxygenate blending (BOB). Previous Argonne studies concluded that blending ethanol to the gasoline pool results in WTW GHG emission reductions [5][10]. Ethanol's desirable features for SI engines (high octane and high heat of vaporization) have generated interest in examining the potential benefit of blending ethanol at higher concentrations to achieve greater GHG emission reductions. For example, Speth et al. [11] showed that using gasoline with 98 RON could reduce annual U.S. gasoline consumption by 3.0%–4.4% in 2040. More recently, Wang et al. [12] conducted a Chinese case study and the results show that relative to E10 gasoline, E30 gasoline could result in a 21.2% reduction of WTW GHG emissions in a turbocharged direct-injection spark-ignition engine vehicle.

- **WG set fuels:** The bio-blendstock for the WG set fuels is produced from woody biomass feedstock via gasification, followed by MeOH/DME conversion to gasoline via Tigas technology [13]. The resultant WG bio-gasoline mainly consists of paraffins and aromatics. It was blended at 9 vol% and 27 vol% with petroleum gasoline BOB to reach 98 RON for the finished gasoline fuels.

- **BR set fuels**: The BR set fuels' bio-blendstock, bioreformate, is aromatic hydrocarbon, mirroring those of refinery gasoline stream reformate, which is a high octane stream produced from a reformer unit. In the present study, the bioreformate is assumed to be produced from cellulosic biomass (corn stover in this study). The bioreformate blendstock used in this study is assumed to be produced by catalytic conversion step aqueous-phase reforming (APR) [14].

- Fuels with composition and properties matching the E, WG, and BR set fuels were blended and tested at ORNL in a Ford 1.6L turbocharged, gasoline direct injected EcoBoost engine in the engine testing and vehicle simulation portions of the U.S.DRIVE and CRC AVFL-20 studies [9] to generate the data that was used in the PTW portion of this WTW analysis.

In particular, this study was designed to answer three questions:

1. How does the production of various high-RON bio-blended gasoline fuel influence overall refinery operation and energy use?

   Refinery LP models were constructed and run to simulate the production of finished gasoline with enforced volumetric bio-fuel blending percentage to meet fuel regulations and requirements in addition to the targeted high octane number specified in this study. This task was conducted Jacobs Consultancy Inc., which has extensive refinery LP modeling experiences with data on crude assays and refining configurations at both regional and national levels.

2. How does the production of high-RON bio-blended finished gasoline fuel influence GHG emissions along the well-to-pump (WTP) gasoline production path?

   On completion of the LP modeling, the refinery operation results were processed and analyzed to obtain information on energy use and refinery onsite GHG emissions (via refinery fuel combustion, intermediate hydrocarbon combustion (e.g., refinery still gas, refinery catalyst coke from fluidized catalytic cracking [FCC]) and CO_2 emissions from SMR). This information was incorporated into the GREET model, which calculates the GHG emissions associated with all upstream stages of fuels produced for vehicle use (e.g., crude oil recovery, transportation, refining, and fuel transportation and distribution).

3. How does the production and use of high-RON bio-blended gasoline fuels impact gasoline GHG emissions along the entire lifecycle of the fuel?

   The WTW analysis has two major parts: upstream well-to-pump (WTP) analysis and pump-to-wheel (PTW) vehicle operation analysis. Vehicle fuel economy and fuel properties link the two stages. The fuel economy was projected by Oak Ridge National Laboratory from separate engine test studies for U.S.DRIVE and CRC, Autonomie simulations; and literature review, which are documented in a report on engine tests of the high-octane bio-blended gasoline fuels and CRC's AVFL-20 report [4][9].

2. Methodology, System Boundary, Key Parameters

WTW analysis of high octane gasoline fuels in this study consists of pathways for petroleum gasoline BOB, corn starch ethanol/corn stover ethanol, wood bio-gasoline and bioreformate gasoline. The WTW system boundaries of these components are shown in Figure 2-1. While bio-ethanol from corn starch dominates current production, corn stover ethanol serves as a surrogate for cellulosic ethanol in the future. Corn stover is also used in BR stream production as a cellulosic feedstock surrogate. For WG stream production, round wood is used as feedstock[13]. The WTW system boundary of each pathway includes feedstock recovery (e.g., crude recovery, corn farming, corn stover collection, and wood collection), feedstock transport, fuel production (e.g., petroleum refining or biomass conversion), fuel transportation and distribution (T&D), and bio-blended finished gasoline combustion in vehicles.

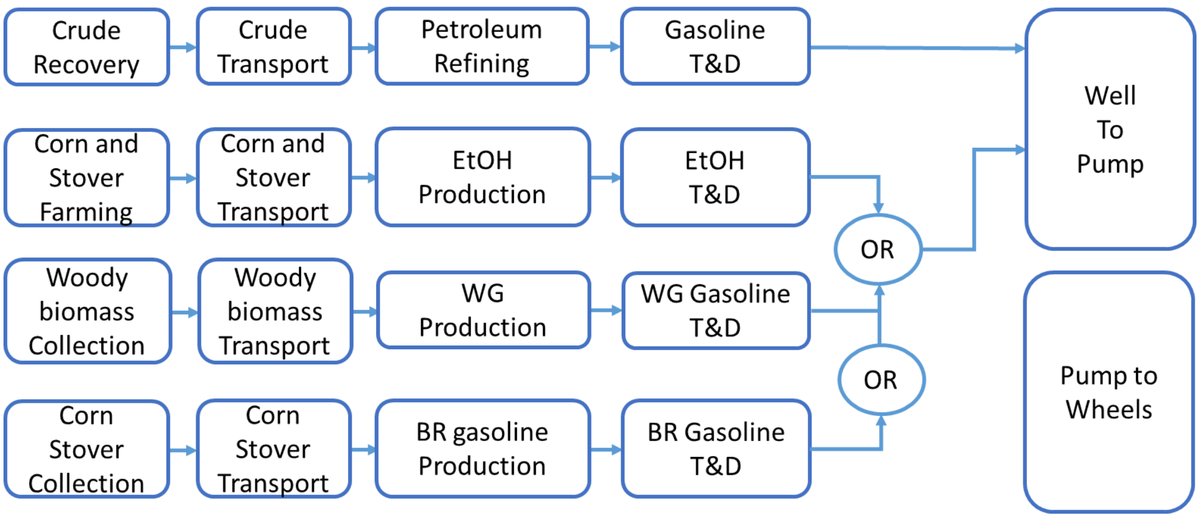


Figure 2-1. System Boundaries for the WTW Analysis of High Octane Bio-Blended Gasoline Fuels

Most of the key stages have been well developed in the GREET model, which is updated annually. In this study, the key WTW input parameters are for the refining process stage that were obtained from refinery LP modeling by Jacobs Consultancy (see Figure 2-2), and for vehicle efficiency that were obtained via Autonomie modeling with inputs from engine test results (see Figure 2-3).

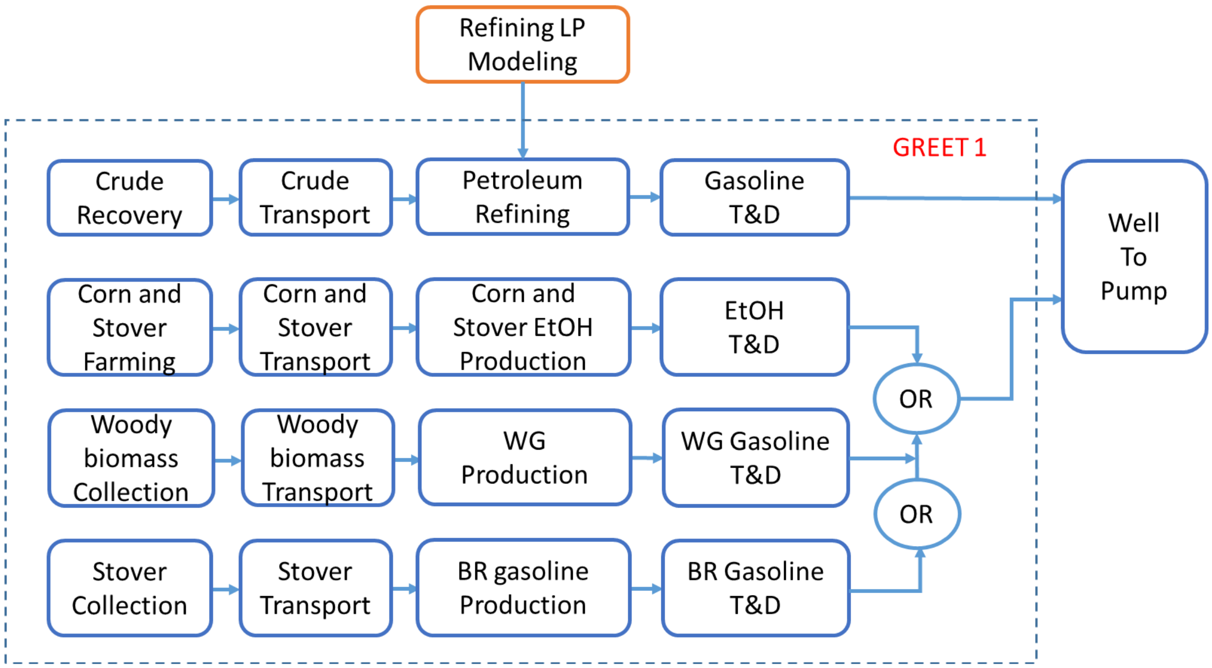


Figure 2-2. WTP Key Stages and Model Sources

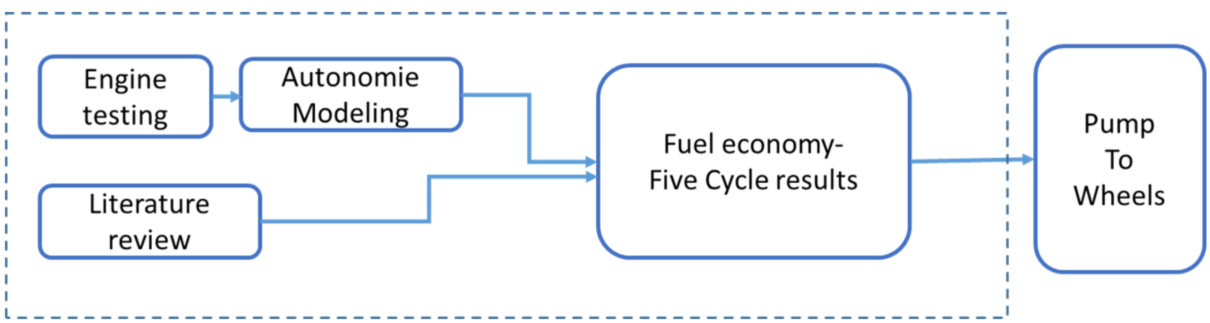


Figure 2-3. PTW Key Stages and Model Sources

For the petroleum refining stage, a petroleum refinery LP model was used to address changes in refinery operations. The key parameters for refinery LP simulation are the bio-blended (finished) gasoline specifications, including octane rating, fuel drivability index (DI), Reid vapor pressure (RVP), sulfur content, aromatic content, benzene content, distillation properties, and others. Some major constraining specifications, such as octane number, RVP and distillation properties, are discussed in detail below.

2.1 Key Specifications for Finished Fuels

Finished gasoline is required to meet federal, state and local fuel specifications, including octane number, vapor pressure (measured as RVP), distillation properties, benzene content, sulfur content, aromatic content (for gasoline in California, mandated by the California Air Resources Board), and others. In this study, octane number, RVP, and distillation properties are the most limiting specifications that often hit the specification constraints for the production of HOFs with different bio-blend blending levels [5].

2.1.1 Octane Number and Sensitivity

Currently for gasolines containing oxygenates, refineries produce semi-finished hydrocarbon products—gasoline BOBs—to be blended with oxygenated biofuel, such as bio-ethanol, to obtain final, finished gasoline products. It is the final finished product, such as E10, but not the BOB, that is regulated and must meet specifications. However, in order to enable the finished products to meet final fuel specifications, the BOBs have to be specifically produced to account for changes after mixing the bio-blendstock, simulated by LP modeling to optimize refinery operations for maximum profits with the finished gasoline specifications as constraints.

The **octane number** of a fuel measures its antiknock property as compared to a mixture of isooctane (with octane number of 100) and n-heptane (with octane number of 0). The higher the octane number, the more compression the air-fuel mixture can withstand before auto-igniting or “knocking” in spark-ignited engines. In many engines, a higher compression ratio is one of the most fundamental paths to improve engine efficiency, which provides an incentive to produce and use high-octane fuels to achieve better fuel economy without engine knock.

Two types of octane numbers are measured: RON and MON [15][16][17]. Both are measured in well-defined, for-purpose test engines. RON is measured by using American Society for Testing and Materials (ASTM) International Test Method D2699, under engine conditions of 600 rpm and an intake temperature of 125°F. MON is measured by using ASTM D2700, under harsher engine conditions of 900 rpm, an intake air temperature of 100°F and intake air-fuel mixture temperature of 300°F. The MON of gasolines is generally lower than the RON. With modern engines operating more frequently at low speed with high load, RON has become a better predictor of engine knock than MON.

In the United States, gasoline is currently characterized and sold by an anti-knock index (AKI), which is calculated as the average of RON and MON as shown below.

$$AKI= (RON + MON)/2 \tag{1}$$

Currently, most conventional U.S. regular grade gasoline has an average AKI of 87, representing approximately 92 RON and 82 MON. With modern engines operating more frequently at low speed with high load, RON has become a better predictor of engine knock than MON.

Another octane related parameter is **octane sensitivity** (OS), which is commonly expressed as

$$OS=RON-MON \tag{2}$$

OS is largely correlated with relative quantities of different fuel components such as aromatics, olefins, and ethanol that have high OS, and saturates that have low OS [18]. For a constant RON, higher OS has been shown to provide greater knock resistance in SI engines and therefore enables greater efficiency [19][20].

Although OS is not a Regulated gasoline specification, for this study, the fuels were also formulated to meet octane sensitivity targets in addition to other commonly regulated specifications to investigate the impact of varying fuel sensitivity on engine performance. The OS targets in turn drive BOB formulation changes and thus refinery operation adjustments. A key goal of the refinery modeling portion of this study was to determine whether the production of BOBs for high-octane bio-blended fuels will likely pose challenges to refinery operations compared with production of current gasolines.

2.1.2 RVP, Distillation and Aromatic/Olefin Content Specifications

Reid vapor pressure (RVP) measures gasoline volatility by the procedure defined in ASTM D323 [21], although this test method has been superseded by techniques compatible with fuels containing water-soluble oxygenates and that are more automated. RVP is regulated by the U.S. Environmental Protection Agency (EPA) during the summer ozone season (June 1 to September 15) to reduce gasoline evaporative emissions that contribute to ground-level ozone. RVP requirements differ for conventional gasoline (CG) and reformulated gasoline (RFG), with the latter having more stringent RVP requirements. For CG, the summer RVP standard is 7.8 psi or 9.0 psi, depending on the state or county [22]. For RFG, the summer RVP standard is approximately 7.0 psi for many U.S. ozone non-attainment areas. In addition, currently, EPA provides a 1 psi waiver for E10 CG during the summer months and many states provide the waiver during the non-summertime period. The RVP is 13 to 15 psi for winter CG, allowing more butanes to be blended in gasoline. For this study, only summer gasoline is investigated, as the RVP constraint makes it more challenging to produce summer gasoline than winter gasoline.

Distillation properties are the gasoline's evaporation profile, measured by the procedure defined in ASTM D86.

Drivability index (DI) is related to the fuel's warm-up driving performance using the temperatures at which the gasoline has evaporated 10 percent (T10), 50 percent (T50), and 90 percent (T90), plus its ethanol content [23]. For many years when most ethanol blends contained no more than 10 vol% ethanol, the DI was calculated as follows:

$$DI°F = 1.5(T10) + 3.0(T50) + (T90) + 2.4\ (\text{ethanol volume percent}) \tag{3}$$

Recently in ASTM D4814 a second equation was introduced for blends containing greater than 10 vol.% ethanol and no more than 15 vol.% ethanol. Although this study includes blends that have up to 30 vol.% ethanol, for simplicity, equation (3) was used to calculate the DI values of all the blends in the refinery modeling study.

The gasoline's volatility properties, including RVP, DI, T10, T50, T90 and others (e.g., vapor-liquid ratio properties) are specified by ASTM D4814. Under this standard, fuel volatility varies for seasonal climatic changes and follows the EPA summer volatility regulations, there are six vapor pressure/distillation classes (named AA, A, B, C, D and E). For all six classes, the maximum DI is between 1200° and 1250°F, the maximum T10 is between 122° and 158°F, the maximum T50 is between 230° and 250°F (with a minimum T50 of 170 °F for E0 fuels and 150 °F for E10 and E15 fuels), and the maximum T90 is between 365° and 374°F.

California has a different set of specifications defined by the California Air Resources Board (CARB) for some gasoline parameters. For example, the CA specification for T50 max is 213°F, rather than the ASTM (national) maximum of 250°F, and CA gasoline's T90 max is 305°F, significantly lower than the ASTM (national) specification of 365-374°F. Some other differences will be discussed in the next section. These have a significant impact on refinery operations and the properties of BOBs (called CARBOBs) and finished gasolines.

Table 2-1 presents the octane, summer RVP and distillation specifications of regular gasoline, premium gasoline, and bio-blended gasolines in various regions that were used for conventional E10 gasoline in the refinery LP modeling of this study. While the RFG summer RVP specification is set at approximately 7 psi for all Regions, the CG summer RVP differs by region. For E10 fuel, a 1 psi waiver is applied to current regulations. However, the 1 psi waiver cannot be applied to blends greater than E10 (e.g., E20 and E30) under current laws. For gasoline fuels with higher ethanol blending, the impact of the 1 psi waiver on refinery GHG emissions would not be significant, because the RVP of a gasoline-ethanol mixture peaks at 5%—10% ethanol blending and decreases with higher ethanol content [6] [24] [25].

Table 2-1. LP Modeling Constraints of Conventional E10 Gasoline for Various PADDs/Regions

Conventional Gasoline E10 Specification	PADD 2	PADD 3	CA
RVP (psi)	10	9	9
RON Min	92	92	92
MON Min	82	82	82
AKI Min	87	87	87
T10 Min (°F)	158.0	158.0	158.0
T50 Min (°F)	170.0	170.0	170.0
T50 Max (°F)	250.0	250.0	250.0
T90 Max (°F)	374.0	374.0	374.0
Drivability Max (°F)	1250	1250	1250
V/L min	122.4	129.4	131.2
Ethanol (vol %)	10	10	10
Olefin Max (vol %)	--	--	--
S PPM Max1	10	10	10
Benzene Max (vol %)	0.62	0.62	0.62
Aromatics Max (vol %)	--	--	--

[1] All gasoline sulfur content conforms to the Tier 3 specification of 10 ppm sulfur.

Note that the LP model for each PADD assumes a constant RVP standard throughout each PADD for simplicity, while in actual practice the RVP specification may vary seasonally at the city, county, and/or state level.

In this study, premium E10 gasoline differs from conventional E10 gasoline only in AKI (other specifications are the same). The 1 psi waiver for RVP is still applied. Currently, E20 and E30 fuels are not prevalent, so there are no regulated specifications. It is assumed that E20/E30 gasoline fuels will adopt the existing specifications for E10 fuels with the possible exception of the RVP spec regarding the 1 psi waiver. Due to this uncertainty, we have assumed that E20/E30 will not have the 1 psi waiver. The resulting LP modeling constraints are shown in Table 2-2.

Table 2-2. Refinery LP Model Constraints of Premium E10 Gasoline and Conventional E20/E30 Gasoline RVP/AKI (other constraints are the same as conventional E10 gasoline)

Constraints for Premium Gasoline E10			
Parameter	PADD 2	PADD 3	CA
RVP (psi)	10	9	9
AKI Min	93	93	91
Constraints for Conventional E20/E30			
RVP (no waiver)	9	8	8

In this study, RFG shares of gasoline pools are set at 15%, 18%, and 88% by volume in PADDs 2 and 3 and CA, respectively, while the remaining gasoline is CG. On average, premium gasoline (AKI 93) is about 10% of the remaining gasoline pool.

Table 2-3 lists the LP refinery model constraints for RFGfor each region. PADD 2 and PADD 3 have similar specifications; however, it is worth mentioning that CA has much more stringent RFG constraints for aromatic content, olefin content, T50, T90, and benzene content.

Table 2-3. LP Model Constraints of E10 RFG Type Gasoline

Constraints for RFG Gasoline E10	PADD 2	PADD 3	CA
RVP (psi)	7.0	7.0	6.95
RON Min	92	92	92
MON Min	82	82	82
AKI Min	87	87	87
T10 Min (°F)	158.0	158.0	158.0
T50 Min (°F)	170.0	170.0	170.0
T50 Max (°F)	250.0	250.0	213.0
T90 Max (°F)	374.0	374.0	315.0
Drivability Max (°F)	1250	1250	1250
V/L min	122.4	129.4	131.2
Ethanol (vol %)	10	10	10
Olefin Max (vol %)	--	--	6.0
S PPM Max	10	10	10
Benzene Max (vol %)	0.62	0.62	0.5
Aromatics Max (vol %)	--	--	16

2.2 Bio-Blend Components and Finished Gasoline Products

The bio-blend components—bio-ethanol, WG blendstock, and BR blendstock—differ significantly in properties. Figure 2-4 summaries some key targeted properties for these bio-blended fuels (finished gasolines) that were produced and tested in the engine test portion of this U.S.DRIVE project.

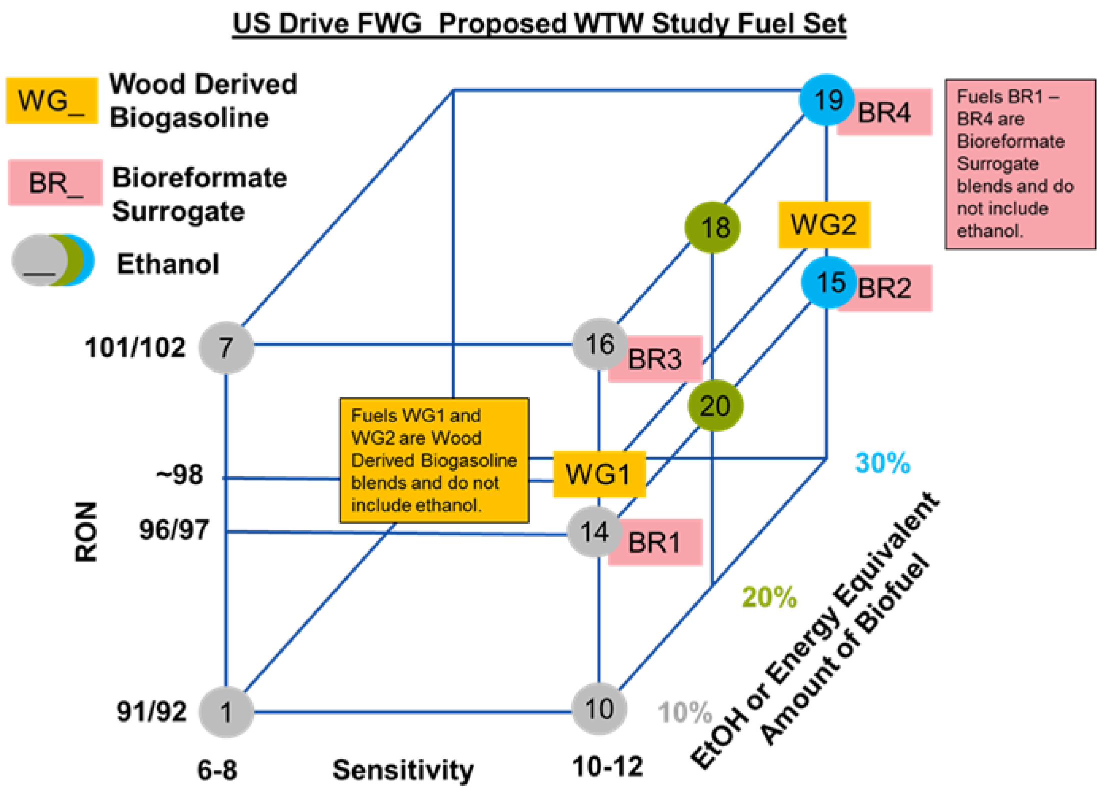


Figure 2-4. Target Properties Matrix for the Studied High-Octane Fuels

For this study, the bio-blendstocks streams used in the fuels for the engine tests were made in a laboratory or at pilot scale, except for the ethanol. Then they were blended with various base gasoline blendstocks by a commercial fuels blender to produce the desired high octane finished gasoline fuels—E set, WG set and BR set. These fuels were used in the engine tests to evaluate engine performance and derive efficiency gains, implemented in ORNL. The properties of the produced fuels can also serve as a guidance for refinery operation and blending.

It should be emphasized that the LP modeling "produced" finished E set, WG set and BR set, but they do not necessarily match the measured properties of the engine test fuels exactly. The procedure used in the LP modeling was to match the RON of LP modeled fuels tightly subject to meeting the other model fuel constraints, including a minimum MON of 82. Special emphasis was placed on matching the RON of LP modeled fuels to the produced fuels (used for the engine tests), as RON is the primary fuel property determining engine knock and efficiency.

The properties of the finished product E set, WG set and BR set fuels produced for the engine test studies were then measured and listed in the following sections, along with the properties of the bio-streams. Note that these are the properties of the fuels blended for the engine studies, but are not the properties of the fuels used in the refinery LP modelling and thus not the properties of the fuels used in the WTW analyses.

2.2.1 E Set Bio-Ethanol Blended Gasoline

Unlike refinery gasoline blending steams, bio-ethanol is a non-hydrocarbon single component. Its physical properties differ greatly from those of most gasoline streams. However, its high octane number (109 RON and 99 MON for neat ethanol) provides a great advantage in boosting the octane of finished gasoline products, although ethanol's low energy content compared to that of hydrocarbons reduces the energy content of blends as the amount of ethanol increases.

This study investigates nine E set fuels that were engine-tested with the measured properties listed in Table 2-4. As noted above, the fuels resulted from LP modeling were matched for targeted RON and meet all specifications, but not necessarily match the exact physical and chemical properties (e.g., aromatic content) of the fuels listed below.

Table 2-4. Properties of Bio-Ethanol and Bio-Ethanol Blended E Set Finished Gasolines Produced for the Engine Tests

Bio-ethanol/ Finished Gasoline	EtOH[3]%	RON	MON	AKI	Sensi-tivity	RVP (psi)	T10 (°F)	T50 (°F)	T90 (°F)	Aromatic (vol%)	Olefin (vol%)
EtOH	100	109[1]	90[1]	99.5	19					0	0
1[2]	10	91.8	84.5	88.2	7.3	8.3	133.4	215.9	327.3	15.8	8.6
10[2]	10	91.4	81.0	86.2	10.4	7.7	134.4	211.0	323.9	23.3	21.1
14[2]	10	96.6	85.5	91.0	11.1	8.3	125.8	184.3	330.3	24.7	9.1
7[2]	10	100.1	92.5	96.3	7.6	7.7	143.0	217.7	275.5	7.6	5.1
16[2]	10	101.1	89.3	95.2	11.8	7.8	137.1	227.0	333.9	28.3	0.4
20	20	97.3	86.6	92.0	10.7	7.3	141.7	167.0	332.0	18.3	1.4
18	20	101.0	89.0	95.0	12.0	7.7	140.7	167.9	335.7	18.2	2.2
15[2]	30	96.5	84.9	90.7	11.6	7.7	142.4	164.4	345.0	16.4	16.2
19[2]	30	101.2	89.2	95.2	12.0	7.2	145.2	164.9	333.5	11.9	1.2

[1] Hunwartzen I. [26]
[2] Sluder et al. [9]
[3] EtOH: ethanol

Table 2-4 lists five E10 fuels, two E20 fuels and two E30 fuels with RON between 91 and 101. E set Fuel 1 and Fuel 10, both E10 fuels, differ in OS because of differences in aromatic and olefin content.

Similarly, both Fuel 7 and Fuel 16 have high RON, at 101, but differ in OS and aromatic/olefin content. We also studied E20 fuels and E30 fuels with higher targeted RON of 96–97 and 100–101 for each ethanol blending level, compared to current specification of 92–93 RON.

2.2.2 WG Set Bio-Blended Gasoline

The fuel properties (laboratory-measured) of the woody gasoline bio–blendstock (WG) and the two blended WG set fuels (WG2 and WG4) that were produced for the U.S.DRIVE engine tests are listed in Table 2-5. The WG stream has a RON of 87.3 and RVP of 12.21 pounds per square inch (psi), exceeding the specifications of commercial finished gasolines, requiring BOBs with high RON and low RVP to balance it out. At a laboratory scale, this challenge resulted in WG2 and WG4 having a high RVP of 10.2 and 9.4 psi for the engine test program, which would not meet specifications of summer CG in PADD 3 and CA. This implies that there will be either change in the volatility properties of WG blendstock or refinery operation challenges in producing BOBs for WG set fuels, which were investigated by LP modeling.

Table 2-5. Properties of WG Blendstock and WG Set Finished Gasoline Fuels Used in Engine Tests

WG/ Finished Gasoline	WG%	RON	MON	AKI	Sensi-tivity	RVP (psi)	T10 (°F)	T50 (°F)	T90 (°F)	Aromatic (vol%)	Olefin (vol%)
WG	100	87.32	81.3	84.3	6	12.21	73.5	195.6	334	26.6	2.5
WG2	9	97.7	87.5	92.6	10.2	10.23	118	225	310	40.6	1.6
WG4	27	97.3	87.1	92.2	10.2	9.42	123	225	310	36.5	0.7

2.2.3 BR Set Bio-Blended Gasoline

The measured fuel properties of the BR bio-blendstock and blended BR set fuels (BR1-BR4) produced for the engine tests are listed in Table 2-6. The BR blendstock, as a highly aromatic mix stream, has a high RON (109) and low RVP (0.2 psi). Four BR blended fuels were investigated, with RON of 97 and 101 and blending levels of 9 vol% and 27 vol%.

Table 2-6. Properties of BR Blendstock and BR Set Finished Gasoline Fuels Produced for Engine Tests

BR/ Finished Gasoline	WG%	RON	MON	AKI	Sensi-tivity	RVP (psi)	T10 (°F)	T50 (°F)	T90 (°F)	Aromatic (vol%)	Olefin (vol%)
BR	100	109.4	99.5	104.5	10	0.2	278	305	348	98.8	0
BR1	9	97.6	87.2	92.4	10.4	7.6	117	212	322	29.6	5.4
BR2	27	97.3	87	92.2	10.3	7.4	139	237	328	29.7	6.3
BR3	9	101.1	90	95.6	11.0	7.6	137	245	328	38.3	3.2
BR4	27	101.0	90.3	95.7	10.7	7.3	147	250	332	37.0	2.3

The RON, MON, and RVP values of the finished BR set gasoline fuels (BR1-BR4 used for engine tests) met the RON, MON and RVP constraints targeted in this study.

2.3 Guidance for Gasoline BOB Properties

As mentioned earlier, the bio-blendstock we studied (neat ethanol, WG and BR) differ greatly in chemical/physical properties and fuel properties and. However, the blended finished fuel products all need to meet the same standard specifications, thus requiring refineries to produce customized BOB “recipes” for each desired fuel product. The base gasoline BOBs used to blend with these bio-blendstock for the U.S.DRIVE and CRC engine tests were analyzed, and the properties are shown in Table 2-7. The BOB properties might serve as a guide or example for refinery operations, even though an individual refinery’s BOB may be the same or somewhat different from those shown here.

Table 2-7. The Properties of Gasoline BOBs in Engine Test Fuels

BOB	Bio-stream%	RON	MON	AKI	Sensi-tivity	RVP (psi)	T10 (°F)	T50 (°F)	T90 (°F)	Aromatic (vol%)	Olefin (vol%)
E set (measured data)											
F1	10	85.6	81.2	83.4	4.4	7.0	135.3	233.7	330.9	17.6	9.5
F10	10	86.4	79.3	82.85	7.1	6.6	141.3	231.4	326.4	25.9	23.5
F14	10	91.8	83.8	87.8	8	7.1	133.7	227.3	334	27.5	10.2
F7	10	94.2	90.3	92.25	3.9	7.0	160.2	220.9	288.6	8.4	5.7
F16	10	97.8	87.6	92.7	10.2	6.4	147.4	232.6	338.2	31.5	0.4
F20	20	86.4	82.2	84.3	4.2	6.4	149.3	252	336.8	22.8	0.5
F18	20	92.3	86.1	89.2	6.2	6.9	147.9	243.4	338.2	24.7	2.1
F15	30	76.8	71	73.9	5.8	6.9	144.6	220.6	359.5	23.5	23.1
F19	30	83.1	80.7	81.9	2.4	6.4	158	230	338.4	17.0	1.8
WG set (estimated data)											
WG2	9	98.7	88.1	93.4	10.6	7.6	133.3	228.2	311.4	42.0	1.5
WG4	27	101.0	89.3	95.1	11.7	6.3	128.2	236.3	304.7	40.2	0.03
BR set (measured data)											
BR1	9	96.1	87	91.55	9.1	8.7	129.7	216.2	327.1	22.6	6.1
BR2	27	91.3	85.6	88.45	5.7	9.9	121.1	193.9	282.5	8.1	10.2
BR3	9	100.4	90.2	95.3	10.2	8.6	133.1	237.6	326.1	32.4	3.5
BR4	27	98.0	89.8	93.9	8.2	10.0	128.4	225.1	307.4	17.6	5.3

The WG bio-blendstock was blended with several hydrocarbon streams (e.g., xylene, base gasoline) at different locations to obtain the finished WG set gasolines, thus there are no physical gasoline BOB streams for WG set fuels to be measured, unlike the cases for BR set fuels. The WG BOB properties were estimated by a simple volume-based linear blending approach. Unlike the E set finished gasolines, the finished WG2 and WG4 fuels have higher RVP than specifications. For refinery operation modeling, the WG2 and WG4 fuels are set to have RVP meeting regional specifications (8 psi for CG in PADD 3 and CA) while the other properties remain unchanged. In other words, LP modeling uses constraints set by regulations or targets meeting or exceeding regulations/targets (RON), not adhere to the measured values of the gasoline fuels used for engine tests. By using the 8 psi specification for the RVP of the finished fuels, WG2 and WG4 BOBs are calculated to have RVP of 7.6 and 6.3 psi, respectively, by using equation (4), 1.25 power law.[7]

$$(\mathrm{RVP})_{mix}^{1.25} = \frac{\sum V_i (\mathrm{RVP})_i^{1.25}}{\sum V_i} \tag{4}$$

As expected, the high RVP of 12 psi for the WG stream would be expected to pose a significant challenges for refineries to produce BOB with correspondingly very low RVP of 6–7 psi and high RON of 98–101 for the blended finished gasolines to meet specifications.

2.4 Bio-Blended Gasoline Market Shares

For this study, bio-blended HOFs are studied for two years, 2022 and 2040, representing near-term and long-term "snapshot" scenarios. Further, the market share of the bio-blended high-octane fuels is assumed to be 50% in 2022 and 100% in 2040. For the three regions studied, historical gasoline grade/types market shares were provided by Jacobs Consultancy. Overall, for all three regions, the premium/regular gasoline share is 10%/90% (projected based on 2015 data). However, the RFG/CG breakout differs in each region, with 15%/85% for PADD 2, 20%/80% for PADD 3, and 88%/12% for CA. Most CA counties are required to use RFG gasolines; however, the CA refineries do provide some CGs to neighboring states.

The tables below list the market share for each type gasoline for the two studied years in each studied region.

Table 2-8. Modeled Gasoline Type Shares of Bio-Blended HOFs in 2022 and 2040

	Note	AKI	RVP (psi)	PADD 2	PADD 3	CA
Year 2022						
CG premium	Current specification	91	8	4.5%	4.0%	0.5%
RFG premium	Current specification	91	7	0.5%	1.0%	4.5%
RFG regular	Current specification	87	7	7.0%	9.0%	39.5%
CG regular	Current specification	87	8	38.0%	36.0%	5.5%
HOF RFG	HOF blend	RON (91/97/101)	7	7.5%	10.0%	44.0%
HOF CG	HOF blend	RON (91/97/101)	8	42.5%	40.0%	6.0%
Total				100%	100%	100%
Year 2040						
CG premium	Current specification	91	8	0%	0%	0%
RFG premium	Current specification	91	7	0%	0%	0%
RFG regular	Current specification	87	7	0%	0%	0%
CG regular	Current specification	87	8	0%	0%	0%
HOF RFG	HOF blend	RON (91/97/101)	7	15%	20%	88%
HOF CG	HOF blend	RON (91/97/101)	8	85%	80%	12%
Total				100%	100%	100%

[7] Equation (4) used by arrangement with Chevron Research Company, ©1971 by Chevron Oil Trading Company [27].

For convenience and brevity, in the following analysis, the business-as-usual E10 gasoline pool includes four gasoline types (CG premium, RFG premium, CG regular, and RFG regular). They are lumped together in the **BAU** gasoline pool. Similarly, the high-octane or **HOF** gasoline pool contains two types of gasoline, HOF CG and HOF RFG. The volume shares of each type are shown in Table 2-8. In 2022, BAU and HOF gasoline have equal shares of 50 vol% each. In 2040, HOF gasoline accounts for 100 vol% of the gasoline market.

3. Petroleum Refinery Linear Programming Modeling Scope and Methodology

3.1 Refinery Modeling Scope and Matrix

The objective of the overall study is to investigate the impact of producing/consuming bio-blended high octane gasoline fuels (including both BAU and HOF gasoline) on GHG emissions and energy use for two future years, 2022 and 2040, representing near-term and long-term "snapshot" scenarios. For comparison, some baseline cases needed to be constructed to present the business-as-usual scenario: the continued use of incumbent E10 gasolines through the years of 2022 and 2040. The base case year of 2015 was also constructed to serve as a starting point to derive fuel production information for 2022 and 2040.

Refinery LP model construction requires considerable amounts of input information and many assumptions. Refinery economics, the objective of LP modeling, is not only governed by refinery operation, but also significantly influenced by global crude oil supply and accessibility (production and transportation), refined products demand, global and domestic economic growth (that impact crude prices and transportation fuels consumption trends), policy implementation (e.g., low sulfur regulation), and so on. At a given refinery, these factors influence the choice of refinery crude slates, refinery product yields and distribution (e.g., gasoline-to-diesel ratio).

For these factors considered, AEO2016 serves as the major reference in this study for prices of crude oils, natural gas and refinery products [2]. AEO2016 also provides key information regarding future refinery product demand and supply, which we considered.

3.1.1 Case Study Matrix

The parameters for the matrix of the simulation were selected by considering regional gasoline supply/demand balance and distribution of refinery configurations as well as capturing near term and long term trends.

Bio-Blended Fuels

Three types of bio-blended fuels, E set, WG set and BR set, with various blending levels and octane demands, as presented in the previous sections, were investigated. For each modeling case, the specific bio-blendstock was introduced into the LP model as an external blending stream with specific properties. With the final product specification varying by region and gasoline grade/type, LP model optimizes the unit operation parameters to produce the BOBs to be mixed with the bio-blend to obtain final products.

Regions: PADD 2, PADD 3 and CA

The United States has five PADDs: PADD 1 (East Coast), PADD 2 (Midwest), PADD 3 (Gulf Coast), PADD 4 (Rocky Mountains) and PADD 5 (West Coast, Hawaii, and Alaska), as shown in Figure 3-1. In this study, three regions (PADD 2, PADD 3, and CA) were studied.

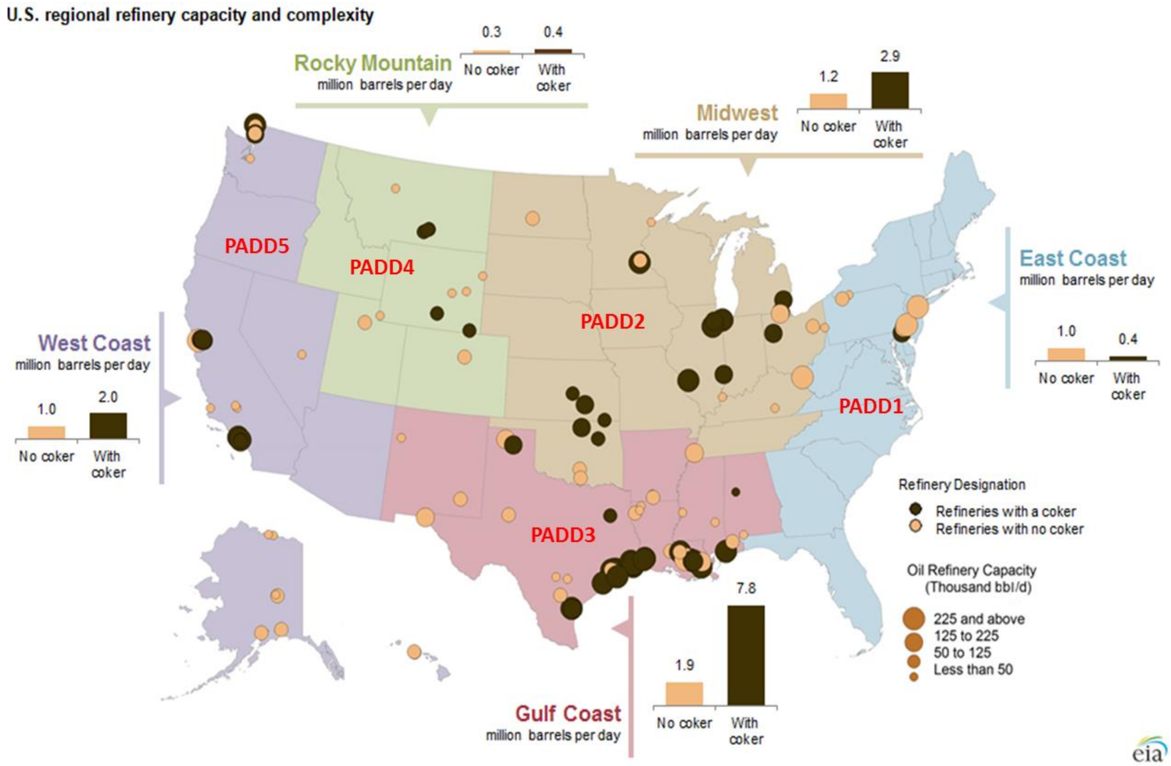


Figure 3-1. U.S. PADDs and Regional Refinery Capacity and Complexity
Source: U.S. Energy Information Administration, "Today in Energy, Regional refinery trends evolve to accommodate increased domestic crude oil production." Last updated January 15, 2015. http://www.eia.gov/todayinenergy/detail.php?id=19591.

PADD 2 and PADD 3 together represent more than 70% of U.S. refining capacity and constitute the majority of the U.S. gasoline supply. PADD 3 was chosen as the major focus because it has more than 50% of U.S refining capacity, although it only consumes one-third of what it produces [28]. It serves as a major gasoline supply region for the United States with a versatile operation reflected by a high Nelson complexity factor of 10.8 [29]. Previous research has shown that PADD 2's response to gasoline specification changes has been similar to PADD 3's [5]. However, PADD 2 receives a large amount of Canadian oil sands products, posing unique refinery operations. Therefore, we also included PADD 2.

In contrast, PADD 1 is mainly a consumption area. PADD 1 represents 8% of U.S. refining capacity and is only 20% self-sufficient of its gasoline demand. PADD 3 supplies the remaining gasoline supply, with occasional international imports [28]. Therefore, this study does not include PADD 1. PADD 4 represents 4% of U.S. refining capacity, and because of its small refinery capacity, the study does not include PADD 4.

PADD 5 covers the largest region. Its geographical isolation and the more stringent fuel specifications in California make PADD 5 mostly self-sufficient, providing about 91% of in-region motor gasoline demand, 96% of jet fuel demand, and 113% of distillate demand [30]. Within PADD 5, California has the majority of the refinery capacity (13% U.S. refinery capacity), has specifications different from the rest of the region, and has the third largest U.S. refinery capacity. California's more stringent transportation fuel specifications and self-sufficiency status warrant separate WTW analyses.

Refinery LP Models: Aggregate Models and Configuration Models

This study includes both aggregate LP models and configuration LP models.

- In an aggregate or notional model, a single refinery model is developed to represent the aggregation of all regional refineries. For this study, an aggregate model was constructed for each of the three regions: PADD 2, PADD 3, and CA.

- A configuration model can be developed to represent a specific refinery configuration type. Four configuration models were developed: cracking (CRK), light coking (LtCOK), heavy coking (HvyCOK), and coking hydrocracking (COKHCK). The configuration models were constructed for PADD 3 and CA only, as PADD 2 refinery configurations are similar to those in PADD 3.

3.2 Refinery Modeling Methodology

As noted above, two types of models, aggregate and configuration models, were constructed to represent refinery industry operations. The former includes regionally aggregated refinery models for PADD 2, PADD 3 and CA, while the latter includes configuration refinery models for PADD 3 and CA only. Previous research found that the refineries in PADD 2 were similar to those in PADD 3, so to streamline the modeling and analyses, configuration models were not developed for PADD 2. In PADD 3, three configuration models (CRK, LtCOK, and HvyCok) were studied; in CA, one configuration (COKHCK) model with an overwhelmingly dominant presence (>90%) in the region was studied. All are based on Jacobs Consultancy information.

In an aggregate or notional model, a single refinery model is developed to represent the aggregation of all regional refineries by examining regional refinery supply macroscopically. This approach might over-simplify the supply scenario by assuming that all interactions among refineries at a unit level in the region are conducted “freely,” without barrier or economic cost, regardless of the different owners/operators of individual refineries. As a result, this over-simplicity often lacks the granularity of analyzing the ease or challenges that a specific refinery configuration would encounter in making various products.

To generate the aggregate models, the capacities of all the process operations for each region were volumetrically summed. For this study, 2014, 2015 and 2016 refinery data, as reported by the Energy Information Administration (EIA), was used as the basis for refinery operations and refined products production[31][32][2]. The EIA data was separated into the PADD regions. Estimates were used to extract the information of sub-Region CA from EIA PADD 5 aggregate data. Other sources, such as reports and data from the California Energy Commission (CEC) and CARB, were also used to construct the CA model. The aggregate models represent the reported feed and production for the aggregate refining centers.

On the other hand, a configuration model can be developed to represent a specific refinery configuration. No two refineries are the same, but their configuration and complexity level can be summarized in several typical configurations dictated by crude slate quality and the desired products. Generally speaking, the heavier (lower API) and more sour (higher sulfur content) the crude slate is, the more complex the refinery configuration will be, to enable a “deeper” conversion.

Four configuration models were constructed and investigated for this study.

- Cracking configuration (CRK) refers to a refinery focused on a FCC unit. The FCC process unit is crucial to converting the heavy part of the crude slate (gasoil) to gasoline products. Usually, the CRK configuration utilizes relative light crude to optimize gasoline production.

- Coking configuration (COK) refers to a more complex configuration including a coker unit in addition to the FCC unit. The coking unit is a deep conversion process which enhances hydrocarbon liquid yield and increase H/C ratio from the given crude slate by rejecting carbon (in the form of petroleum coke). This enables the conversion of low value crude bottoms (residuals) to more valuable products (e.g., gasoline and diesel) by providing intermediate feedstock (coker gasoil) to the FCC unit. The inclusion of a coker unit generally equips a refinery to process a heavier, sourer and thus discounted crude slate to maximize profits. In this study, two COK configurations, LtCOK, and HvyCOK configurations, were investigated, with different unit capacity and the ability to process different crudes, with the latter processing heavier and sourer crudes.

- The coking-hydrocracking configuration (COKHCK) is also complex, by virtue of having an additional hydrocracking unit to convert crude bottoms. In this study, the COKHCK configuration represents a typical CA refinery. A hydrocracker unit is BAUarded as a diesel or distillate oriented process (but also yields gasoline and other products) by converting the heavy part of crude slate to diesel products via hydrogen aided cracking.

To summarize, CRK, LtCOK, and HvyCOK are representative configurations for PADD 3, and COKHCK presents a typical refinery in CA.

3.3 Development of Refinery LP Models

Key input information for the LP models' construction is summarized and listed in this section. It is worth mentioning that all the cases presented in the main report do not include capital expansions. Some cases including capital expansions are presented in Appendix 5.

3.3.1 Base Case Construction

Our baseline models are business-as-usual cases, with fuels meeting current regulations or imminent upcoming regulations (e.g., Tier 3, a 10 ppm sulfur content for gasoline that was mandated in 2017). More specifically, the baseline cases in this study refer to E10 fuels with various grades and types (regular and premium; CG and RFG). Some key parameters for developing baseline LP models are crude slates, prices of crude, energy and material inputs (e.g., NG and electricity, purchased butane), and petroleum product portfolios and prices. The baseline models for future years were used as a reference points to assess the impacts of various future scenarios.

It is worth mentioning that the current models do not include additional hydrotreating for marine diesel or marine bunker oil due to two factors. First, there is a lack of process and demand information; second, the low sulfur emissions from marine fuels combustion in the long term are commonly projected to be achieved by post-combustion treatment, scrubber process, or LNG vessels.

3.3.1.1 Assumptions for Crude Slate and Other Refinery Inputs for Each Region

Assumptions for these key parameters are summarized below. In general, the quality of the crude supplied to U.S. refineries can be categorized into light sweet (LTSWT), light sour (LTSWR), medium sweet (MDSWT), medium sour (LTSWR), heavy sweet (MDSWT) and heavy sour (LTSWR). Crude slate is based on reported data of crude imports (EIA) and domestic crude (various sources). We estimate the overall quality by putting these crudes into the above six quality categories. Specific assays were used in this process, for example, Maya was used to represent HVYSWR import from Mexico. This methodology results in crude slates consistent with reported EIA regional crude quality. The shares of each crude type are shown in Table 3-1, which summarizes the aggregate regions with respect to crude slate inputs and regional average crude API gravity and sulfur content for the years 2015, 2022, and 2040.

Table 3-1. Reported U.S Refinery Crude Oil Shares in 2015 and Modeled U.S. Refinery Crude Oil Shares in 2022 and 2040 (provided by Jacobs Consultancy)

	PADD 2 (Vol%)			PADD 3 (Vol%)			CA (Vol%)		
Crude type	2015	2022	2040	2015	2022	2040	2015	2022	2040
LTSWT	54%	35%	33%	28%	31%	30%	0%	0%	0%
LTSWR	0%	0%	0%	0%	0%	0%	22%	23%	21%
MDSWT	0%	0%	0%	0%	0%	0%	29%	20%	16%
MDSWR	8%	2%	2%	27%	26%	16%	8%	9%	10%
HVYSWT	0%	0%	0%	0%	0%	0%	0%	0%	0%
HVYSWR	38%	63%	65%	45%	43%	54%	42%	48%	53%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%
API gravity	33.2	28.8	28.4	31.6	32.3	30.7	26.9	26.3	25.5
Sulfur (%)	1.6	2.2	2.2	1.9	1.8	1.9	1.5	1.6	1.6

Similarly, the key crude input information for the configuration refineries is summarized in Table 3-2.

Table 3-2. Crude Slates for Different Configuration Models for 2015, 2022 and 2040 (unchanged with years) (from Jacobs Consultancy)

	CRK	LtCOK	HvyCOK	COKHCK
LTSWT	85%	34%	15%	0%
LTSWR	0%	0%	0%	20%
MDSWT	15%	0%	0%	40%
MDSWR	0%	9%	20%	0%
HVYSWT	0%	0%	0%	0%
HVYSWR	0%	57%	65%	40%
Total	100%	100%	100%	100%
API gravity	42.6	31.3	26.2	27.1
Sulfur (%)	0.4	2.0	2.8	1.3

Other assumptions used in the LP modeling are briefly described here. Hydrogen is assumed to be supplied by SMR of natural gas and the catalytic reformer unit. Energy is sourced from natural gas along with supplementary sources, such as refinery fuel gas and coke deposited on FCC catalysts. The lower heating value (LHV) of the refinery fuel gas is estimated by using the GREET default value, 51 MJ/kg. The FCC coke is estimated to have 86.7% carbon content by using GREET default value. In addition to the key gasoline specifications listed in Section 2, the models produce all diesel fuels as ultra-low-sulfur diesel with 15 parts per million (ppm) sulfur content.

3.3.1.2 Refinery Product Demand and LP Model Yields

Table 3-3 summarizes the crude inputs and refined products from the 2015 baseline, which are consistent with the projected refinery product yield/demand in *AEO2016*. The production, capacity, and configuration of the 2015 calibration model were used as the basis for generating new baseline refinery models for future years, using EIA forecasts for refinery input and production. EIA's AEO forecast of U.S. demand growth rates was applied to the 2015 data to develop the refinery production targets for 2022 and 2040. The models produced target volumes to meet U.S. demand and allowed for gasoline and diesel exports.

Table 3-3. U.S. Refinery PADD Base Cases LP Modeling Refinery Products Yields

Crude Type	PADD 2 (MMgal/day)			PADD 3 (MMgal/day)			CA (MMgal/day)		
	2015	2022	2040	2015	2022	2040	2015	2022	2040
LPG	96,301	94,102	49,129	535,178	365,598	267,954	96,601	32,800	-7,237
Gasoline	2,148,782	2,055,210	1,633,365	4,425,355	4,251,702	3,974,579	965,736	1,004,612	758,610
Jet fuel	242,765	252,344	294,441	844,469	907,087	1,012,926	302,213	309,297	347,253
Diesel	1,070,173	1,218,219	1,330,465	2,850,562	3,372,796	4,055,886	366,573	395,808	716,287
Fuel oil	213,495	221,732	236,076	458,575	460,325	496,585	87,271	106,351	103,605
G/D	2.01	1.69	1.23	1.55	1.26	0.98	2.63	2.54	1.06

The gasoline-to-diesel (G/D) ratios for 2022 and 2040 were derived from 2015 production data. Starting with regional production in 2015, EIA projected growth rates were used to estimate production in 2022 and 2040. Gasoline-to-diesel ratios were then calculated from this production data.

3.3.1.3 Assumptions for Energy Prices and Refinery Product Prices

Table 3-4 presents four sets of prices for benchmark crudes and major refinery products for this study, using information from the *AEO2016* reference case. For the products whose prices were not provided by EIA forecast, various numerical methods were used to estimate the prices to produce the so called "empirical" prices. For example, the price of low sulfur diesel was estimated by using a ratio or discount to the EIA ULSD (ultra-low sulfur diesel) price.

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, normally the price spread between gasoline and diesel could potentially drive refinery operation changes; however, the fixed gasoline/diesel volumetric (G/D) ratio forecast by AEO made the operation options independent of price spread while still influencing refinery profit. In other words, in this study it is the fixed G/D volume ratio, not the price spread that drives the refinery operation options.

Table 3-4. Refinery LP Modeling Price Assumptions

	Units	Basis	2015	2022	2040
Marker Crudes					
WTI (USGC)	$/bbl	EIA	48.7	78.7	129.1
Brent (USGC)	$/bbl	EIA	54.3	86.7	138.2
Refined Products					
Natural Gas	$/MMBtu	EIA	2.6	4.4	4.9
Normal Butane	¢/gal	Empirical[8]	100.3	119.5	170.6
Isobutane	¢/gal	Empirical	105.2	125.3	178.9
Propane	¢/gal	EIA	111.8	148.8	192.9
Propylene	¢/gal	Empirical	170.0	202.5	289.1
Naphtha	¢/gal	Empirical	183.4	218.4	311.9
CG BAU	¢/gal	EIA	187.9	223.8	319.6
CG Prem	¢/gal	Empirical	205.8	245.0	349.9
RBOB BAU	¢/gal	Empirical	192.0	228.6	326.5
RBOB Prem	¢/gal	Empirical	209.8	249.8	356.8
Jet Kerosene	¢/gal	EIA	146.7	224.9	360.6
Low S Diesel	¢/gal	Empirical	165.1	232.8	368.3
No. 2 Oil	¢/gal	Empirical	162.1	228.5	361.5
Ultra-Low Sulfur Diesel	¢/gal	EIA	167.2	235.8	373.0
1.0%S Residual oil	$/bbl	Empirical	42.4	82.4	129.3
3.0%S Residual oil	$/bbl	Empirical	39.5	76.8	120.5

(AEO2016 reference case Table 12) (https://www.eia.gov/outlooks/aeo/data/browser/#/?id=12-AEO2016&Region=0-0&cases=ref2016&start=2013&end=2040&f=A&linechart=ref2016-d032416a.3-12-AEO2016~ref2016-d032416a.28-12-AEO2016&ctype=linechart&sourcekey=0)

3.3.1.4 Other Key Influencing Factors

Gasoline-to-Diesel Ratio

One notable change across the period is the projected decrease in gasoline demand and the increase in distillate (jet and distillate fuel oil that includes diesel) demand. The G/Distillate and G/Diesel ratio is projected to decrease significantly, shown in Figure 3-2. The reduction in gasoline demand and the increase in distillate demand could lead to changes in conversion operations (e.g., less FCC, more hydrocracking), reduced internal hydrogen supply (from reformer) and increased hydrogen demand via SMR for diesel production.

[8] The EIA forecast does not provide prices for all the products produced in the LP modeling. We use various numerical methods to estimate the prices of those products not provided by the EIA.

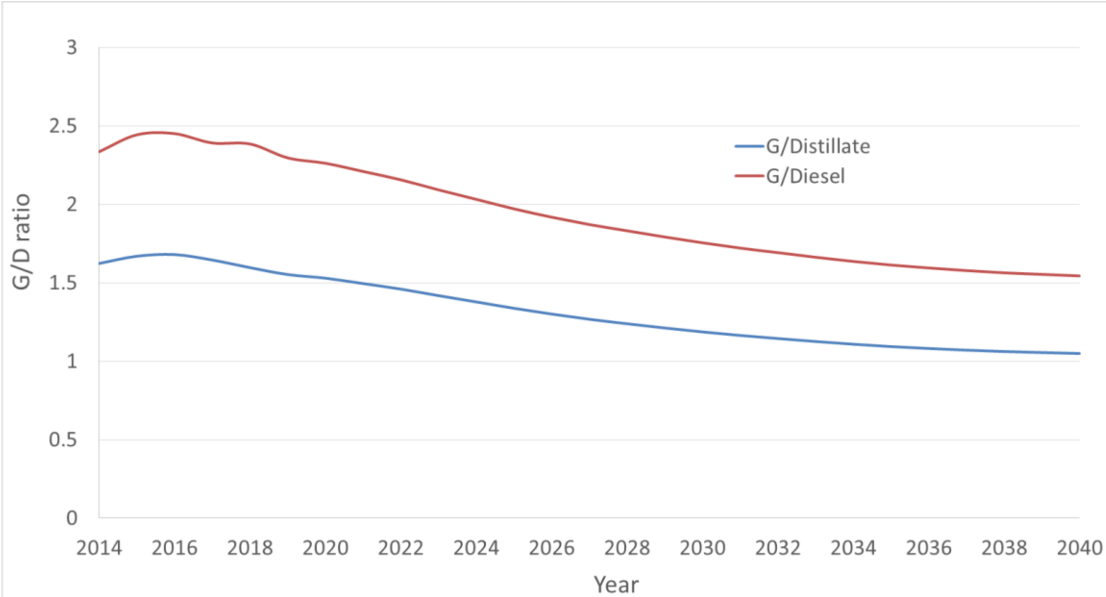


Figure 3-2. Pojected U.S. Overall G/D Ratio Change Over Time (Based on AEO2016)

Natural Gasoline

There is some interest in using “natural gasoline” (natural gas liquid) in refineries as a feedstock. This study does not consider the prevalent usage of natural gas plant liquid/natural gasoline/natural gas liquid/condensate in refineries, as it is likely that these materials go to petrochemical plants (mainly cracking) instead of refineries, as indicated by *AEO2016*, page IF-32 to IF-33 [2]. AEO states that if the NG to oil price spread is high in the United States, the values of natural gas liquid will grow quickly and can be exported. If the price spread is low, drillers will drill dry wells instead of wet wells, and the growth of natural gas liquid will slow down.

Under current practice, these liquids are generally not favored in refineries because of high vapor pressure (too high for blending) and low reactivity (probably can only feed into isomerization unit). However, it is possible natural gas liquid may have an indirect impact on naphtha sales/export price and LPG sales prices. While this could have an impact on refinery LP modeling, it is beyond the scope of this study.

3.3.2 Case Constructions for Bio-Blended HOFs

Compared to the base case constructions (both aggregate and configuration models) for each PADD, the cases of the bio-blend HOFs need some additional modeling inputs, adjustments and refinements.

3.3.2.1 Modeling Tactics

In this study, the refinery LP model seeks the maximum profit to be obtained from specified finished products by optimizing operation/purchase/blending, but without capital investments in refining operations. The study models the finished products instead of BOBs to allow consistent regional specifications for all cases while addressing gasoline RVP regional variations, and to give the models more optimization flexibilities. Meanwhile, it is observed that for meeting the projected more stringent gasoline specifications (for RON and sensitivity), LP modeling resulted in fewer feasible cases. Thus, this study focuses on the investigation of RON, rather than both RON and sensitivity. In terms of LP modeling, the model matches desired high RON tightly, but lets MON float, but with a minimum MON of 82 based on current specification. Overall, the specifications used in LP modeling either match or exceed current values posed by regulations/requirements.

As bio-blend streams (the bioblendstocks), ethanol, woody biomass gasoline and bioreformate are not produced within refineries but are introduced to the LP modeling system as purchased blending streams with well-characterized properties. Although LP modeling has blending calculation/optimization capabilities, the different blending properties of the ethanol stream and gasoline BOBs require some research and external calculations to aid blending.

3.3.2.2 Inclusion of BR Blendstock in LP Modeling

We discuss bioreformate for blending first, as they are hydrocarbons and thus have properties closer to refinery BOBs.

One well-defined "purchased" BR bio-stream can be introduced in the LP modeling for blending optimization to produce BR1, BR2, BR3 and BR4 finished gasolines with 9%, 27%, 9% and 27% BR content, respectively, by varying refinery operations to produce the BOBs required to produce finished gasolines meeting defined model constraints. The BR blendstock is a mixture of hydrocarbons within the petroleum gasoline range, so a volumetric linear combination approach was used to estimate the mixture's octane numbers. This approach is widely used in LP refinery modeling.

In Table 3-5 below, some key features of the BR blendstock are listed and compared to those of refinery petroleum blending streams.

Table 3-5. Blending Values of RON, AKI, and RVP for Various Gasoline BOB Components and Bio-Blend BR and WG Stream

	Octane				
Blending Stream	RON	MON	Sensitivity	AKI	RVP (psi)
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
WG biogasoline*	87.2	81.3	6	84.3	12.2
BR bioreformate *	109.4	99.5	10	104.5	0.21

*These are the measured values of the blendstocks used to make the engine test fuels.

3.3.2.3 Inclusion of Ethanol Stream in LP Modeling

In contrast to the BR and WG cases where the biocomponents are all hydrocarbons, calculating of the ethanol blending with refinery BOBs poses significant challenges, due to the non-linear blending feature of ethanol with hydrocarbons.

Ethanol has different blending RONs for E10, E25 and E40, as shown in previous studies [5][10][33], and is also highly dependent on BOB compositions that include aromatics, olefins, and paraffins [34][35][36]. The non-linear blending is especially pronounced with BOBs with high isoparaffin/low aromatic content. For example, Zhang and Sarathy [35], using nonlinear blending equations developed by Anderson et al. [33], showed that ethanol was calculated to have a blending RON of 145 and blending MON of 114 for BOBs with low aromatic content (RON of 95 and MON of 85), compared with the 109 RON for neat ethanol.

Some researchers describe the sensitivity of ethanol blending RON to gasoline BOB properties as a synergistic effect from paraffins and naphthenes and an antagonistic effect from aromatics [34][37].

Many previous studies have reported ethanol blending RON values for BOBs with relatively narrow aromatic content (about 25–35 vol%). However, the E set fuels in the present study have a very large aromatic content variation, from 7% to 28%, raising a concern about applying one fixed ethanol blending RON to all E set modeling cases.

The investigation of the non-linear volume blending properties of ethanol by modeling is beyond the scope of this study. As a solution, for this study, instead of using a fixed value of ethanol blending RON for all ethanol blended gasoline fuels, a linear correlation equation to calculate the ethanol blending RON as a function of BOB aromatics content was introduced into the LP modeling. The equation parameters were obtained via regression from lab-measured RON values of the finished gasoline and the RON of BOB gasolines for the fuels used in the engine study. Compared with the 109 RON of neat (pure) ethanol, the iterated ethanol blending RON of the “purchased” ethanol stream (of the nine E set fuels) is ranged between 131 and 153 (see Figure 3-3).

The blending RON of ethanol depends on BOBcomponents, and in refinery modeling the opposite can also be true: The optimized BOB components will depend on the ethanol blending RON (how many octane numbers ethanol can contribute to the finished gasoline pool). Thus, an iteration approach was used in LP modeling to achieve the ethanol blending RON.

Other ethanol blending properties, such as MON, were estimated by back-calculations (the MON difference between finished gasoline and BOB gasoline), and are listed in Table 3-6. Correlation between ethanol blending MON and aromatic content was weak, thus the blending MON values determined in the engine study for each ethanol-containing fuel were used in the LP model.

For the WG gasoline and bioreformate gasoline blending, the properties (RON, MON and RVP) of the neat bio-blendstockwere adopted for the blending values. This is appropriate because bioreformate streams are hydrocarbons (chemically non-distinguishable from their petroleum counterparts), and thus are assumed not to show noticeable non-linear blending behavior with gasoline BOBs as observed for ethanol.

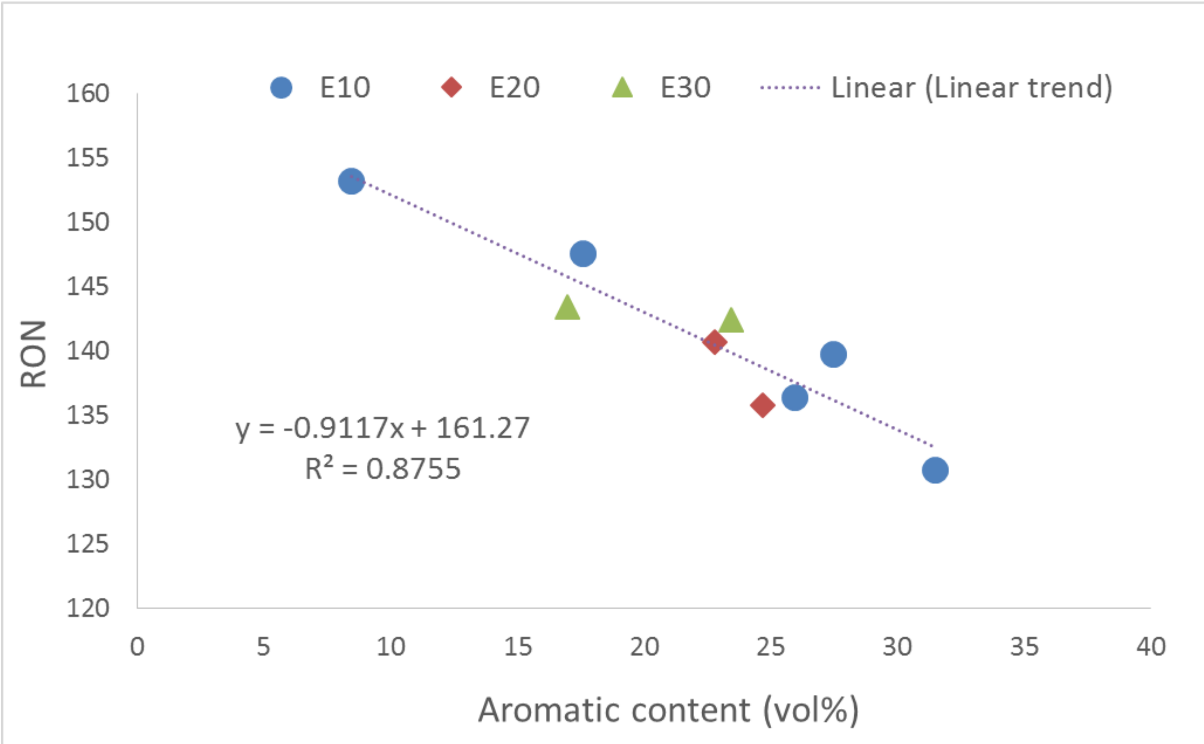


Figure 3-3. Correlation of Ethanol Blending RON and Aromatic Content, Customized Ethanol Blending RON Via Back-calculation.

Table 3-6. Blending Values of RON, AKI, and RVP for Various Gasoline BOB Components and Bio-Blend Ethanol, BR and WG Stream

	Content	Measured BOB Data			Measured Finished Gasoline Data				Derived Data for EtOH/BR/WG		
Fuel	Vol%	RON	MON	RVP	RON	MON	RVP	Sensitivity	RON	MON	RVP
F1	10	85.6	81.2	7	91.8	84.5	8.3	7.3	147.6	114.2	20.3
F10	10	86.4	79.3	6.6	91.4	81	7.7	10.4	136.4	96.3	18.1
F14	10	91.8	83.8	7.1	96.6	85.5	8.3	11.1	139.8	100.8	18.8
F7	10	94.2	90.3	7	100.1	92.5	7.7	7.6	153.2	112.3	13.5
F16	10	97.8	87.6	6.4	101.1	89.3	7.8	11.8	130.8	104.6	19.5
F20	20	86.4	82.2	6.4	97.3	86.6	7.3	10.7	140.7	104.1	10.9
F18	20	92.3	86.1	6.9	101	89	7.7	12	135.8	100.6	10.9
F15	30	76.8	71	6.9	96.5	84.9	7.7	11.6	142.5	117.3	9.4
F19	30	83.1	80.7	6.4	101.2	89.2	7.2	12	143.4	109	8.9
BR1	9	96.4	86	8.3	97.6	87.2	7.6	10.4	109.4	99.5	0.2
BR2	27	92.8	82.4	10	97.3	87	7.4	10.3	109.4	99.5	0.2
BR3	9	100.3	89.1	8.3	101.1	90	7.6	11.1	109.4	99.5	0.2
BR4	27	97.9	86.9	9.9	101	90.3	7.3	10.7	109.4	99.5	0.2
WG2	9	98.7	88.1	10	97.7	87.5	10.2	10.2	87.3	81.3	12.2
WG4	27	101.1	89.3	8.4	97.3	87.1	9.4	10.2	87.3	81.3	12.2

3.3.2.4 Pricing of Bio-Streams and HOF Gasoline Fuels

Without fixing the percentage, or "share", of the biocomponent in the finished gasoline, the pricing of bio-blendstock "purchased" and HOF sold can influence LP modeling economics, and thus refinery operation. However, for this study, the refinery operation is not impacted by the pricing of bioblendstock and HOF because the model forces a fixed share of bioblendstock to be blended and fixed amounts of HOF fuels to be produced. In other words, the LP model seeks maximum profitability within the constraints of the blending level. The scope of the study is to examine the potential WTW GHG emissions and energy use in producing and consuming HOF. The primary scope of LP modeling is to probe refinery capability to provide these HOF fuels, with economic factors being secondary. Thus, research on and discussion of pricing impacts are not presented here. If economic study becomes a research focus, more research on pricing of these bio-blendstock and HOF will be needed.

4. WTW Analysis Approach, System Boundary, and Key Parameters

In this section we focus on the key stages for WTW analyses. The WTP boundary of this study including both the petroleum pathway and the biofuel pathways, is shown in Figure 4-1. The petroleum pathway includes crude recovery/transportation, refining, fuel T&D, and vehicle operations. The biofuel pathway includes farming, collection, fertilization production, conversion process, and biofuel T&D. Information on the refinery operation stage was provided from LP model runs by Jacobs Consultancy; all the other stages were analyzed with the GREET[1] 2016 model. Process overview, key assumptions, and data inventory for each stage are given below.

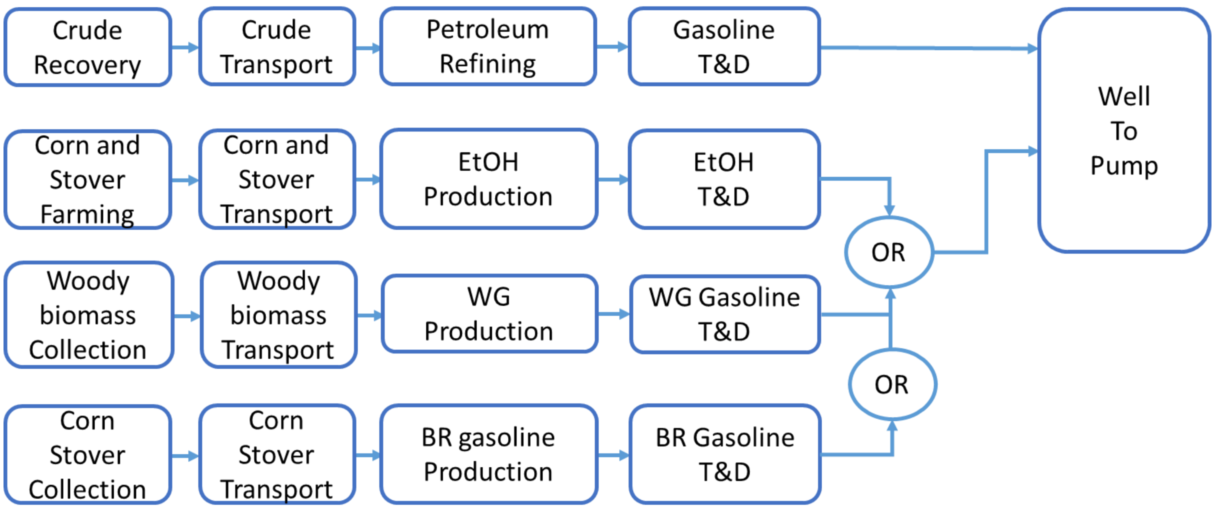


Figure 4-1. WTP System Boundaries

4.1 Crude Recovery

U.S. refineries process crude oils from diverse sources with various qualities, depending on crude supply and price, refinery capability, transportation accessibility, economics and other factors. Overall, the crude slate aggregated in each PADD or region differs from the others, greatly influenced by transportation accessibility along with economic factors.

The GREET 2016 model categories crude oils into several categories based on geographic location and crude recovery technology: Canada (oil sands and conventional crude), Mexico, the Middle East, Latin America, Africa, and other regions, as well as domestic crude oils (shale oil and conventional crude). Generally, the geographic location and recovery technology greatly influences GHG emissions, and the typical energy consumption and GHG emissions for crude recovery and transportation for each category have been established and documented previously by Argonne. The projected shares of crude oils used by refineries in PADD 2, PADD 3 and CA are listed in Table 4.1 below for 2015, 2022, and 2040.

Table 4-1. Categorized Crude Input Information for the Studied Regions in 2015, 2022 and 2040

	PADD 2 (Vol%)			PADD 3 (Vol%)			CA (Vol%)		
Crude type	2015	2022	2040	2015	2022	2040	2015	2022	2040
U.S. Conventional	4%	4%	4%	49%	51%	51%	49%	44%	42%
U.S. Shale	37%	32%	30%	14%	15%	15%	0%	0%	0%
Canadian Conventional	21%	2%	2%	0%	0%	0%	0%	0%	0%
Canadian Oil Sands	38%	62%	64%	4%	3%	9%	3%	4%	4%
Mexico	0%	0%	0%	10%	10%	12%	0%	0%	0%
Middle East	0%	0%	0%	13%	11%	1%	30%	31%	32%
Latin America	0%	0%	0%	10%	10%	12%	19%	21%	22%
Africa	0%	0%	0%	0%	0%	0%	0%	0%	0%
Other	0%	0%	0%	0%	0%	0%	0%	0%	0%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%
API gravity	33.2	28.8	28.4	31.6	32.3	30.7	26.9	26.3	25.5
Sulfur (%)	1.6	2.2	2.2	1.9	1.8	1.9	1.5	1.6	1.6
Domestic	41%	36%	34%	63%	66%	66%	49%	44%	42%
Bakken	20%	19%	21%	0%	0%	0%	0%	0%	0%
Eagle ford	71%	69%	68%	22%	23%	23%	0%	0%	0%
Other U.S. domestic (conventional)	10%	11%	12%	78%	77%	77%	100%	100%	100%

The information for 2015 is based on historical data (EIA website, CEC information [3]), while the information for 2022 and 2040 is based on projections by EIA in AEO2016 [2] and other sources.

Table 4-2. Crude Input Information for Configuration Refineries in the Studied Regions in 2015, 2022 and 2040

	CRK	LtCOK	HvyCOK	COKHCK
U.S. Conventional	45%	65%	20.0%	0.0%
U.S. Shale	55%	7.0%	45.0%	0.0%
Canadian Conventional	0.0%	0.0%	0.0%	15.0%
Canadian Oil Sands	0.0%	0.0%	0.0%	20.0%
Mexico	0	28%	10.0%	0.0%
Middle East	0	0%	20.0%	0.0%
Latin America	0	0%	5.0%	0.0%
Africa	0.0%	0.0%	0.0%	0.0%
Other	0.0%	0.0%	0.0%	25.0%
Total	100.0%	100.0%	100.0%	100.0%
API	42.6	31.3	26.2	27.1
Sulfur	0.4	2	2.8	1.3
U.S. Domestic				
Domestic	100%	72%	35%	65%
Bakken	0%	0%	0%	0%
Eagle ford	55%	10%	14%	0%
Rest of United States	45%	90%	86%	100%

Note: For the configuration models, the same crude slate was used for all three studied years.

AEO2016 [2] projects that from 2015 to 2040, the share of Canadian heavy oil and domestic shale oil will continue to increase, at the expense of decreasing imported crude oils elsewhere. This will not only impact the energy use and GHG emissions of the crude recovery stage in the WTW analysis, but will result in changes in refining activities due to the operation adjustments needed to accommodate the crude quality change. This will, in turn, produce product-specific efficiency changes, as shown in a previous study [29].

With the increasing importance of Canadian oil sands for U.S. fuels production, research efforts had been made to analyze the energy use and GHG emission intensities associated with the various oil sands recovery and upgrading operations [38][39]. The GHG emission results from Cai et al. was implemented in the GREET simulations [38].

The GHG emissions of the U.S. petroleum industry are impacted ont only by increasing utilization of oil sands, but also by increasing utilization of domestic shale oil. The parameters for shale oil recovery are based on the energy intensity and GHG emissions provided in Brandt et al. [40] and Ghandi et al. [41] for Bakken and Eagle Ford in Table 4-3 below.

Table 4-3. Key Parameters for Crude Recovery of Conventional Crude and Shale Oil [40][41]

Parameter	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

Unlike oil sands recovery, shale oil recovery has energy efficiency similar to or even slightly higher than conventional crude does. However, the shale oil recovery stage, especially Bakken oil recovery, is associated with gas flaring, leading to its higher GHG emission intensities compared with conventional crude.

GHG emissions associated with crude recovery, using GREET 2016 with the default values, are shown in Table 4-4. The GHG intensities of conventional crude oil recovery in this study are based on default parameters in GREET 2016, which was based on previous research on conventional crude recovery [42].

Table 4-4. Crude Recovery (including crude transportation) GHG Emissions (from GREET 2016 Default Values)

		Oil Sands: Surface Mining		Oil Sands: In-Situ		Shale Oil	
Crude type	Conventional	Dilbit	SCO	Dilbit	SCO	Bakken	Eagle Ford
g/MJ crude	8.5	14.4	29.5	22.6	33.2	9.8	5.3

Compared with conventional crude, oil sands with various recovery/upgrading technology show notable higher GHG emissions. Therefore, the oil sands share in the crude mix is a key parameter for WTW results of petroleum fuels.

4.2 Biofuel Production

This section summarizes the key parameters for production of the ethanol stream and BR stream.

4.2.1 Ethanol Production

Corn ethanol is currently used as a blending component to produce regular and premium gasoline (E10). However, with technology advancement and process improvement, cellulosic feedstocks are projected to play a role in providing future bio-ethanol. The cellulosic feedstocks could be sourced from crop residues (e.g., corn stover, wheat straw, and rice straw) or dedicated energy crops (e.g., switchgrass, miscanthus, mixed prairie grasses, and short-rotation trees). Ethanol in the E set fuels (CRC AVFL-20 fuels and FWG fuels: E10, E20 and E30) are not bound to any specific production pathways. That is, the source of ethanol is irrelevant for engine testing but is important for the WTP portion of the life-cycle analysis. Therefore, this study examines the lifecycle results of ethanol produced from corn stover (as a surrogate for cellulosic source) and corn starch, which will serve as the lower and upper bounds in estimating GHG emissions for ethanol production.

Figure 4-2 shows the system boundary of corn ethanol and corn stover ethanol production, including the major stages of ethanol lifecycle analysis. Table 4-5 summarizes key WTW parameters for corn starch and corn stover ethanol pathways for this study, primarily from the analysis by [43] with a number of subsequent updates that track technology advancement and information availability. Some examples include corn farming and fertilizer applications [44]; process updates regarding corn ethanol production [45]; corn oil extraction in dry milling corn ethanol plants [46]; and integrated corn starch/corn stover ethanol production [47]. Another important update regarding ethanol production from corn starch/corn stover is the study carried out by Qin and Canter et al. [48] and Qin and Dunn et al. [49] on how land use changes impact GHG emissions of ethanol production pathways, varied by tillage practice, corn stover removal rate, and organic matter input techniques (i.e., cover crop and manure applications).

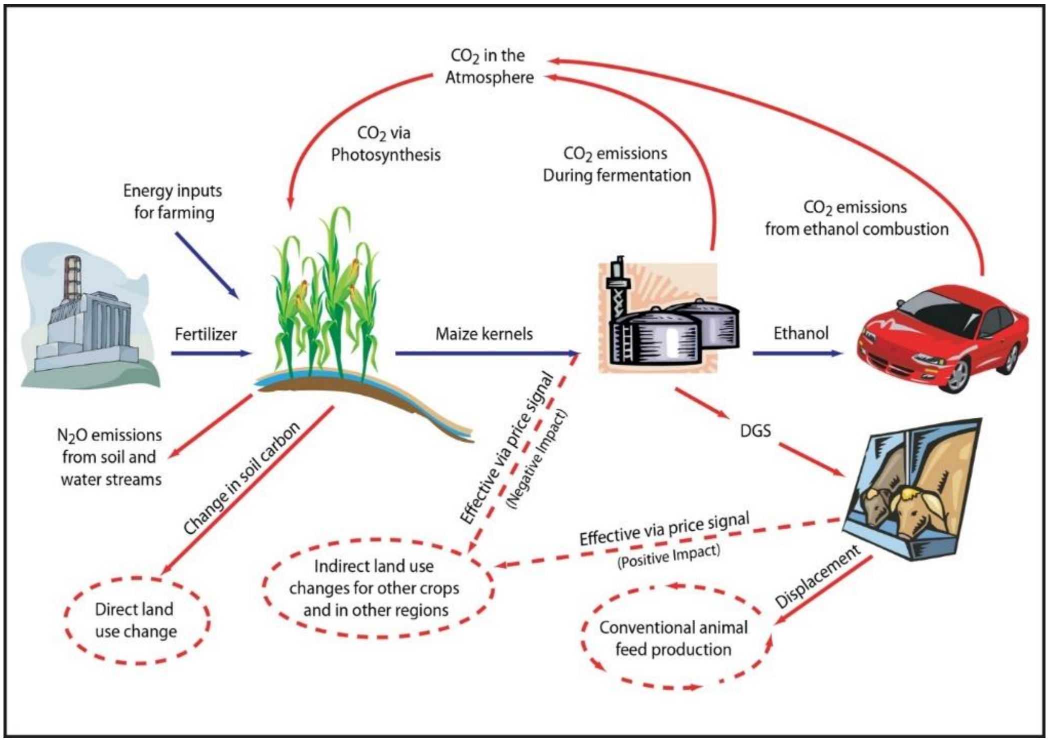


Figure 4-2. System Boundary of Corn Ethanol Production

The key parameters for the major stages of corn starch ethanol production and corn stover ethanol production are listed in Table 4-5.

For the corn farming stage, corn stover has much less fertilizer use than corn starch does, due to the marginal allocation of resource consumption between corn starch and corn stover. In other words, the main product, corn starch, was assigned with the most burdens, as corn starch production is the purpose of corn farming. Only resources specifically used for corn stover were assigned to it, including energy use for corn stover collection and transportation, and supplementary fertilizer application after stover collection. It is worth mentioning that such allocation option might change in the future if corn stover is used in quantity to make ethanol and the relative values of corn starch/corn stover change.

During the production stage, there are two key differences in ethanol production between corn starch and corn stover. First, the corn stover ethanol production process is assumed with zero fossil energy use, since the lignin portion of stover can provide needed steam for plant operation. In contrast, corn ethanol plants do require high fossil energy consumption, with natural gas as the primary source to provide needed steam. Second, the corn stover ethanol process co-produces and exports electricity, while the corn starch ethanol process co-produces Distiller' Grains with Solubles (DGS), Corn Gluten Meal (CGM) or corn oil. Ethanol from both corn starch and corn stover receives credits for these co-products, displacing incumbent conventional products.

Table 4-5. Key WTW Parameters for Corn Starch and Corn Stover Ethanol Pathways (in GREET 2016)

Corn farming/corn stover collection (per dry tonne of corn starch or corn stover, except as noted)

Parameter	Corn Starch Grain	Corn Stover
Direct energy use (MJ)	288	223
N fertilizer application (kg)	15.08	7.70
P fertilizer application (kg)	5.48	2.20
K fertilizer application (kg)	5.76	13.20
Limestone application (kg)	50.79	0.00
N_2O conversion rate of N fertilizer (%)	1.225%	0%[1]

Corn starch/corn stover ethanol production

Parameter	Dry Mill without Corn Oil Extraction	Dry Mill with Corn Oil Extraction	Wet Mill	Cellulosic Corn Stover
Ethanol yield (L/dry MT of corn grain or corn stover)	426	429	398	353.9
Ethanol plant fossil energy use (MJ/L of ethanol)	7.49	7.36	13.22	0.00
DGS yield (dry kg/L of ethanol)	0.675	0.642		
CGM yield (dry kg/L of ethanol)			0.147	
CGF yield (dry kg/L of ethanol)			0.632	
Corn oil yield (dry kg/L of ethanol)		0.023	0.117	
Electricity yield (kWh/dry MT of corn stover)				205
Enzyme use (g/dry kg of corn grain or corn stover)	1.144	1.144	1.144	12.144
Yeast use (g/dry kg of corn grain or corn stover)	0.396	0.396	0.396	2.739
Corn starch ethanol shares (%)	17.7%	70.9%	11.4%	

[1] This is because nitrogen input from corn stover otherwise remained in cornfields and from supplement fertilizers is equal, the net N2O emissions from supplement fertilizes are therefore zero.

Some other key assumptions regarding corn starch- and corn stover-to-ethanol production are listed in Table 4-6.

Table 4-6. Selected WTW Parameters for Corn Starch and Corn Stover Ethanol Pathways

Land Management Scenario*	None
Corn Stover Removal Rate per acre	30%
Yield Modeling Scenario	Yield increase
Land Management Practice for Corn Grain and Corn Stover Production	Conventional Tillage
Inclusion of CO_2 Emissions from Land Use Change	Both domestic and foreign
Allocation Method	Attributional (marginal)

*In GREET 2016, See Qin and Canter et al. [48] and Qin and Dunn et al. [49]

For biomass-derived biofuels, CO_2 emissions due to land use change, whether positive or negative, can be an important factor. A comparison of the effects of land use change on corn stove and corn starch CO_2 emissions is shown in Table 4-7.

Table 4-7. The CO_2 Emissions from Land Use Change for Corn Starch and Corn Stover Ethanol

	Corn Starch		Corn Stover	
Unit	Domestic	Foreign	Domestic	Foreign
(g/gal EtOH)	208	424	-14	-37
(g/MJ EtOH)	2.58	5.26	-0.17	-0.46

4.2.2 WG Set Gasoline Production

WG set gasoline production is omitted in the WTW analyses as all the LP modeling cases of aggregate models and configuration models were found to be not feasible and were not included in further WTW analysis in this study.

4.2.3 Bioreformate Blendstock Production

The process flowscheme for BR bioreformate production was based on techno-economic analysis results from National Renewable Energy Laboratory (NREL) [14]. The major steps in the conversion process are summarized in Figure 4-3.

In BR stream production, the first process step is “feed handling and preparation” to size the corn stover feedstock. In the next step, pretreatment and conditioning, the sized feedstock is treated with dilute sodium hydroxide for deacetylation, then further treated with dilute sulfuric acid to convert most of the hemicellulosic carbohydrates in the feedstock to soluble sugars. When further treated with ammonia conditioning, the pH of the whole pretreated slurry is raised to prepare it for enzymatic hydrolysis.

At the enzymatic hydrolysis (or enzymatic saccharification) step**,** cellulose is converted to glucose by using cellulase enzymes (produced onsite). The resultant hydrolysis slurry, containing glucose and other sugars from hemicellulose hydrolysis during pretreatment, is then filtered and purified in the purification and concentration step. Insoluble solids (from unreacted or re-condensed biomass components) are removed and routed to boilers for combustion for energy supply. The hydrolysate is further concentrated, filtered and ion-exchanged to remove ions that could cause catalyst deactivation in the next steps.

For the conversion stage, the NREL study modeled the diesel production pathway to convert purified and concentrated hydrolysate to hydrocarbons through four catalytic reactor steps: hydrogenation, APR, condensation, and hydrotreating.

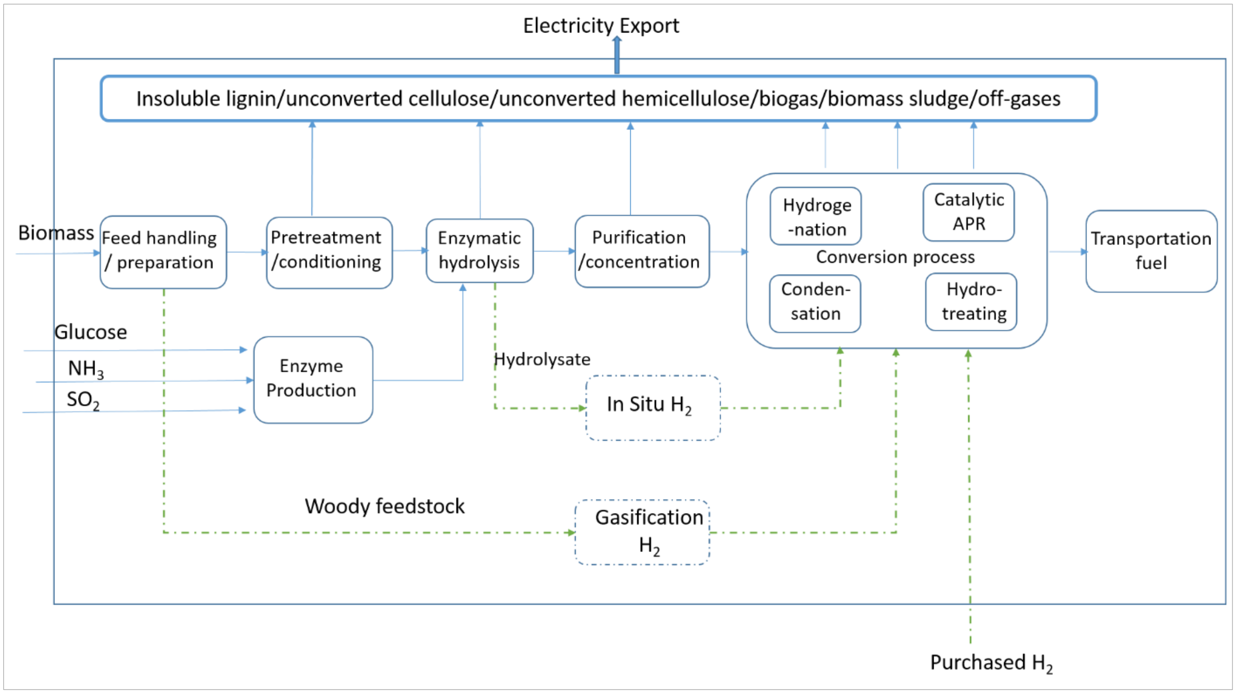


Figure 4-3. BR Production System Boundary and Major Stages

As the first conversion step, the hydrogenation reactor reduces sugars to sugar alcohols (e.g., sorbitol, xylitol) or other polyols (e.g., glycerol, ethylene, or propylene glycol). The sugar alcohols are fed to the APR unit, which reduces the oxygen content of the feedstock and produces hydrogen, carbon dioxide, light alkanes, and oxygenates. These intermediate oxygenates are reacted at the condensation step to extend the carbon chain length to form diesel range fuel, and the organic liquid stream is further hydrotreated to form diesel-like fuels.

All four reactions in the conversion stage require hydrogen. The source of hydrogen supply is a key parameter impacting GHG emissions and will be discussed in three scenarios below.

Purchased Hydrogen

The option of purchasing external hydrogen was set as the base case in the NREL study. The study specified that the purchased hydrogen is produced via SMR of fossil natural gas. With this option, the base case had a high carbon yield from hydrolysate through finished fuels. However, it has a tradeoff between high fuel yield and GHG emissions attributed to natural gas use in SMR. CO_2 from the fossil source was co-produced with hydrogen chemically and is accounted for in the GHG emissions along with the CO_2 emissions due to fuel combustion.

In-situ Hydrogen Production

The in-situ APR-H_2 process can be integrated into the main catalytic sugar reforming process for hydrocarbon fuel production (the APR step in the conversion stage). In this process, hydrogen is supplied from renewable source by converting a fraction of the hydrolysate produced from enzymatic hydrolysis, sugar concentration and cleanup, at the expense of lowered hydrocarbon fuel yield. An optimal splitting ratio of 41% hydrolysate for hydrogen production balances reducing fossil carbon and maintaining overall fuel yields.

$$\text{Hydrolysate (glucose, xylose, etc.} + H_2O) \rightarrow H_2 + CO_2$$

In this process, the co-produced CO_2 is biogenic as the hydrolysate is derived from biomass.

Gasification Hydrogen Production

Another method of producing renewable hydrogen is to gasify a fraction of biomass feedstock in a separate gasification process.

$$\text{Biomass} + H_2O \rightarrow H_2 + CO + \text{Char}$$

As the gasification process favors woody biomass feedstock over herbaceous feedstock (e.g., corn stover) with lower ash and higher carbon content, a mixture of corn stover and woody biomass was used to feed the biorefinery in this modeling scenario. In contrast, the other two scenarios, with purchased hydrogen and in-situ hydrogen production, have only corn stover as biomass feedstock. The overall feedstock amount is the same for all three scenarios—purchased hydrogen, in-situ hydrogen production, and gasification hydrogen— but different liquid fuel volumes are produced.

The gasification process produces syngas and other bi-products: tars (CxHy), methane, and light hydrocarbons [50]. A tar reforming process was also included to reform tars, methane, and light hydrocarbons to additional syngas. The overall hydrogen yield of this process is 82 kg H_2/dry tonne biomass.

$$\text{Char} + CH_4 + C_xH_y + H_2O \rightarrow CO + H_2$$

It is important to mention that the NREL model in Davis et al. [14] focused on diesel/naphtha fuel production, while this study focuses on BR stream production, which is in the gasoline range. The two pathways share some common steps and differ in some other conversion processes, illustrated in Figure 4-4 below.

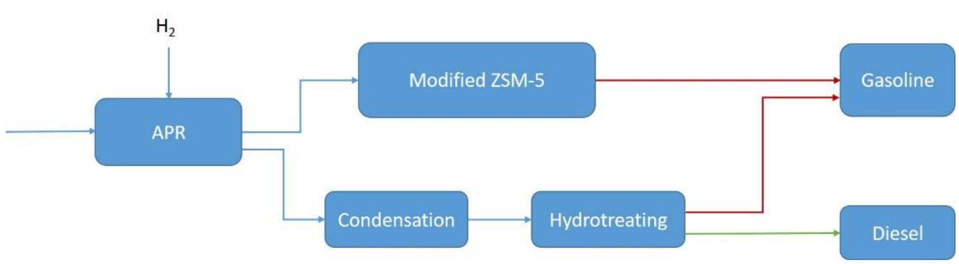


Figure 4-4. Pathways for Producing Gasoline and Diesel Via APR and Subsequent Conversion Processes (http://www.virent.com/technology/)

In the Davis et al. study [14], the diesel and naphtha (gasoline blending stock) were produced in the hydrogenation-APR-condensation-hydrotreating step (hydrogenation was not shown in the diagram). In contrast, the BR stream is mainly produced via the APR-ZSM-5 conversion pathway.

With the absence of the ZSM-5 conversion process data, the diesel conversion pathway process data were used to estimate the GHG emissions and energy use of BR bio-gasoline production.

Adopting the diesel production process data for estimating BR bioreformate production is expected to have minor impact on overall lifecycle GHG emission estimates of BR production. In fact, it may serve as a more conservation estimate with higher GHG emissions, because the combination of condensation and hydrotreating processes is likely to have higher GHG emissions than the ZSM-5 conversion catalyst, due to the hydrogen demand in the former. It is often observed that hydrogen demand is a key contributor to GHG emissions.

Byproducts of the BR biofuel production process can be combusted to produce electricity and steam and to reduce solid waste disposal. These byproducts include insoluble lignin and the unconverted cellulose and hemicellulose from the feedstock, biogas from anaerobic digestion, biomass sludge from wastewater treatment, and off-gases from the conversion/upgrading operations.

Key material and energy inputs are shown in Table 4-8.

Table 4-8. Key Material and Energy Inputs for BR Bioreformate Production (Based on Davis et al. [14])

Parameter	Purchased H_2	In-situ H_2	Gasification H_2
Fuel yield (MJ/MT feedstock)	8,393	4,851	5,597
Fuel yield (gal/ton)	62.17	35.93	41.46
Self-supplied electricity (Btu/gal)	19,884	No data	No data
Electricity import (Btu/gal)	NA	888.2	NA
Electricity export (Btu/gal)	6,204	NA	1,393
Sulfuric acid (g/gal)	368.7	637.2	501.4
Caustic (NaOH) (g/gal)	231.4	399.9	231.4
Ammonia (g/gal)	51.0	88.2	50.9
HCl for IX regeneration (g/gal)	184.7	319.2	184.6
Caustic for IX regeneration (g/gal)	105.4	182.0	105.2
Purchased H_2 (g/gal)	633.3	-	-
APR catalyst (g/gal)	1.3	1.7	1.3
Condensation catalyst (g/gal)	0.5	0.6	0.5
Polymer (g/gal)	0.3	0.6	0.3
Ammonia (g/gal)	17.9	36.4	26.7
Boiler chemical (g/gal)	0.0	0.1	0.1
FGD lime (g/gal)	29.6	52.3	29.6
Cooling water chemical (g/gal)	0.3	0.6	0.5
Glucose (g/gal)	199.7	345.0	199.5
Corn steep liquor (g/gal)	13.7	23.6	13.6
Corn oil (g/gal)	1.2	2.0	1.0
Host nutrients (g/gal)	5.6	9.7	5.7
Sulfur dioxide (g/gal)	1.3	2.3	1.3
Ammonia (g/gal)	9.5	16.5	9.5
Gasifier train chemicals (g/gal)	NA	NA	24.4

The GHG emissions associated with the production of these material/energy inputs are included in GREET already. The land use change impact on GHG emissions was also accounted for, and is -0.604, -1.044, -0.905 g/MJ for the three approach Purchased H_2, in-situ H_2 and gasification H_2, respectively.

The resultant bioreformate consists of 99% aromatics, resulting in properties different from those of conventional BOB. See Table 4-9.

Table 4-9. BR Bioreformate Properties

	BR Bioreformate Lab Test Results*	GREET Default Value for gasoline BOB
Heating value (Btu/gal)	128,357	116,090
Density (g/gal and g/L)	3,306.9 (0.8736)	2,819 (0.7447)
Carbon content	90.9 wt%	86.3 wt%

* Measured properties of the simulated bioreformate surrogate blended as the BOB for the BR gasolines tested in the engine study.

5. Refinery LP Modeling Results

The LP modeling work of refinery operations for producing E set fuels, WG set fuels and BR set fuels (along with other refinery products) for various regions, refinery configurations, and years was conducted by Jacobs Consultancy [51]. The results were analyzed further and summarized here.

5.1 LP Modeling Results for E Set Fuels

A feasible solution summary of LP modeling cases in PADD/Region refinery models with E set fuels production is shown in Table 5-1. As mentioned earlier, cases were not run for the E-set fuels in PADD 2. It is also worth emphasizing that the LP modeling included the constraint that additional capital investment in refinery operations was not allowed. Additional refinery capital investment may allow infeasible solutions to be come feasible, however research for this specific goal was not investigated. Some capital expansion cases were shown in Appendix 5 with goals of seeking alternative gasoline BOB production processes with potential economic benefits.

A feasible solution exists when a model can find a solution for the given constraints and conditions of the model. An infeasible solution occurs when a model cannot solve given the constraints of the model. For example, if the model is commanded to make "X" BPD of gasoline, and there is no combination of operations in the model to produce the "X" BPD, this will result in an infeasible solution.

Table 5-1. Feasible Solution Summary of PADD LP Modeling Cases

Year	2022			2040		
Region	PADD 2	PADD 3	CA	PADD 2	PADD 3	CA
Base Cases	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible
Fuel 01 E10 Low RON	N/A	Feasible	Feasible	N/A*	Feasible	Feasible
Fuel 07 E10 Hi RON	N/A	Feasible	Feasible	N/A	Infeasible	Infeasible
Fuel 10 E10 Low RON	N/A	Feasible	Feasible	N/A	Feasible	Feasible
Fuel 14 E10 Mid RON	N/A	Feasible	Feasible	N/A	Feasible	Feasible
Fuel 15 E30 Mid RON	N/A	Feasible	Feasible	N/A	Feasible	Feasible†
Fuel 16 E10 Hi RON	N/A	Feasible	Infeasible	N/A	Infeasible	Infeasible
Fuel 18 E20 Hi RON	N/A	Feasible	Feasible	N/A	Feasible	Feasible†
Fuel 19 E30 Hi RON	N/A	Feasible	Feasible	N/A	Feasible	Feasible†
Fuel 20 E20 Mid RON	N/A	Feasible	Feasible	N/A	Feasible	Feasible†

Notes:
*N/A—not applicable.
†Feasible, but would require California to change regulations and allow higher than 10 vol.% ethanol.

5.1.1 Aggregate LP Modeling Base Case Results

Base case PADD-level aggregate models in PADD 2, PADD 3 and California refineries producing BAU fuels were created for 2022 and 2040. The detailed refinery products of these base cases are shown in Appendix Table A1-1. Some key modeling results are summarized in this section.

5.1.1.1 Export Gasoline Amount

The PADD refinery models not only produce gasoline for domestic use, but also export gasoline. The export mechanism can be used as an outlet for the “excess” gasoline BOB produced in U.S. refineries as a result of decreased domestic demand, for example, as a result of a domestic G/D ratio decrease or bio-blend share increase.

The export gasoline is assumed to meet the gasoline specification in Mexico, which has a sulfur limit of 30 ppm (vs. 10 ppm in the United States), a benzene limit of 1.0% (vs. 0.63% in the United States), without ethanol content, and the same octane ratings as U.S. regular grade gasoline. The export gasoline/total gasoline ratios for all PADD refinery base cases are shown in Figure 5-1.

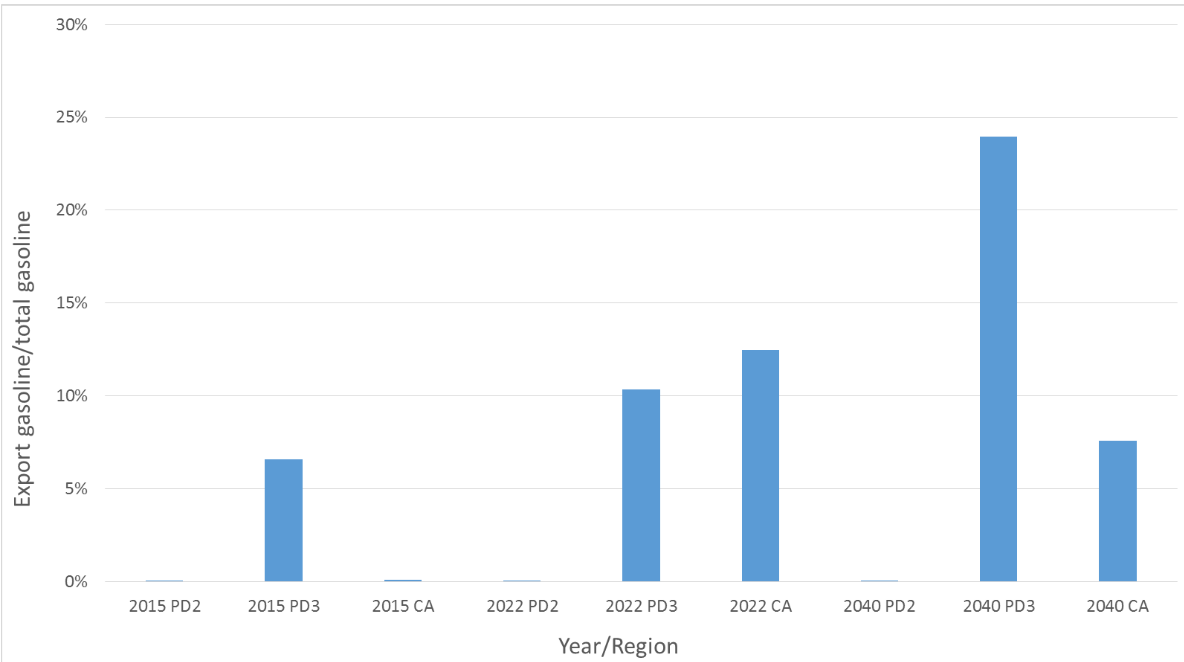


Figure 5-1. The Export/Total Gasoline Ratios for PADD 2, PADD 3 and CA Refineries in Three Years in Base Cases

In 2015, the PADD 2 and CA refineries had minimal gasoline export, and PADD 3 exports are about 7%. In 2022, gasoline export increases to 10% for the PADD 3 refinery and 13% for the CA refinery, driven by the lower G/D ratio in the EIA projection. In 2040, a further decreased G/D ratio results in 24% export by PADD 3 and 7% export by CA. It might be because with the decreasing G/D ratio the CA Region goes to a strong diesel production mode. Gasoline exports decrease, at the same time there is an offsetting increase in diesel exports.

5.1.1.2 Components of Base Case Gasoline

The PADD refinery LP modeling yields gasoline fuels with various component shares for the base case, shown in Figure 5-2.

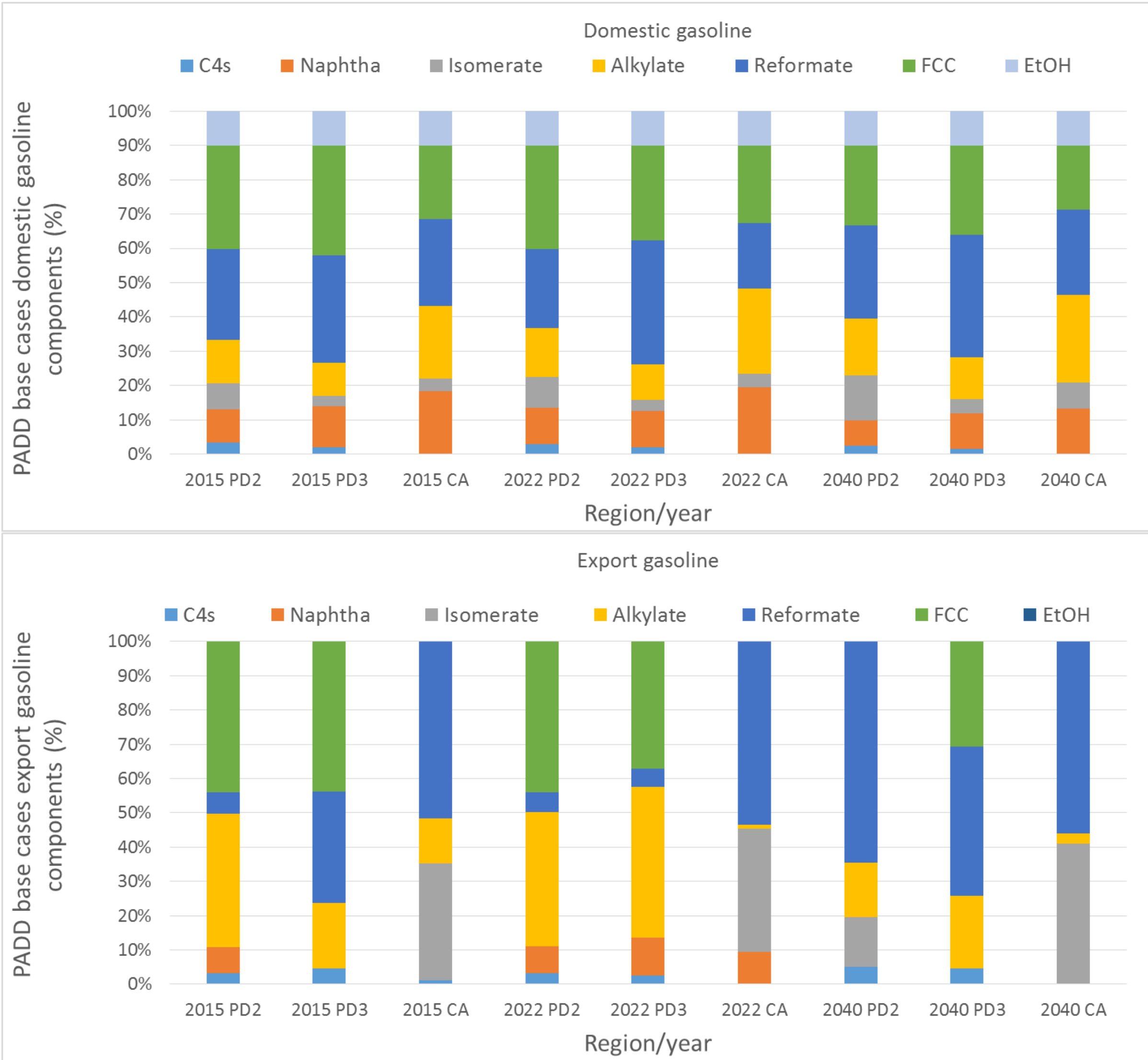


Figure 5-2. PADD/Region Base Case Gasoline (Domestic and Export) Components for Three Years

The figure shows that PADD 3 Regional refineries mainly blend gasoline with reformate and FCC streams, while CA refineries blend gasoline with FCC streams, reformate and alkylate. From 2022 to 2040, the gasoline components in PADD 3 have minor changes, while the gasoline components in CA change noticeably, with increased reformate share and decreased FCC share. For each baseline E10 gasoline set, domestic gasoline and export gasoline vary significantly in component shares.

<u>5.1.1.3 Reformer Severity and Reformate Volume of Base Case Gasoline</u>

Reformate plays an important role in refineries, not only by bringing a high-volume high-octane stream to the gasoline pool but also the flexibility to adjust octane number (with the tradeoff of volume). Reformate is an important refinery component with high octane numbers, and the reformer unit has some flexibility in tuning the product octane range, called severity. Higher severity can boosts product octane numbers by increasing the amount of aromatics; however, this has the drawback of shrinking product volume due to the higher density of aromatics.

Some key elements of reformer severity and reformate volume in PADD 2, PADD 3 and CA are shown in Table 5-2.

Table 5-2. PADD Base Case Refinery Reformer Severity and Reformate Volume

Unit Operations	2015 PADD 2	2015 PADD 3	2015 CA	2022 PADD 2	2022 PADD 3	2022 CA	2040 PADD 2	2040 PADD 3	2040 CA
Total Reformate (bbl/day)	674,555	1,617,760	291,389	544,898	1,680,475	272,313	521,597	1,785,089	235,578
Avg* Reforming Severity	90.0	90.7	95.3	90.0	90.0	92.2	90.0	90.4	92.1
Sev × BPD (1000 bbl/day)	60,710	146,764	27,765	49,041	151,243	25,094	46,944	161,423	21,695

*Avg: average

The table shows that California refineries have higher reformer severity than PADD 2 and PADD 3 refineries. In addition, from 2015 to 2022 and 2022 to 2040, the reformate contribution to the gasoline pool (severity × BPD) is projected to increase in PADD 3 and decrease in PADD 2 and California. Reforming severity increases commonly indicate that refinery operation is changing in order to meet octane demand. Although the reforming severity increase has the benefit of an octane boost, it is coupled with gasoline volume shrinkage as reformate volume decreases and an increased reformate boiling point.

5.1.1.4 Hydrogen Demand/Supply for Base Case Gasoline

Hydrogen plays an essential role in modern refineries. It is widely used in various hydrotreating units to produce “clean” products (low sulfur fuels), in addition to assisting conversion reactions in the hydrocracking unit and isomerization unit. Although a reformer can co-produce hydrogen to supply internal needs, significant hydrogen demand is typically met by using a SMR plant, which reacts natural gas with steam. The projected supply of hydrogen from reformers and SMR is shown in Figure 5-3.

From 2015 to 2022 and 2022 to 2040, the hydrogen supply, corresponding to refinery hydrogen demand, is projected to increase the least in PADD 2 and the most in CA. For each refinery base case, the hydrogen supply from the reformer is observed to be similar, and the hydrogen produced from SMR fulfills the rest of the demand.

The CA refineries have much higher hydrogen demand, which might be attributed to one or both of two reasons: First, CA refineries use very heavy crudes (low API), requiring hydrogen’s aid to convert heavy crudes to valuable lighter fuels (gasoline, diesel, etc.). Second, hydrocrackers, which are present in most CA refineries, require additional hydrogen.

Some refineries can purchase hydrogen if internal production is not sufficient. In the present work, all the modeling results show sufficient internal hydrogen supply.

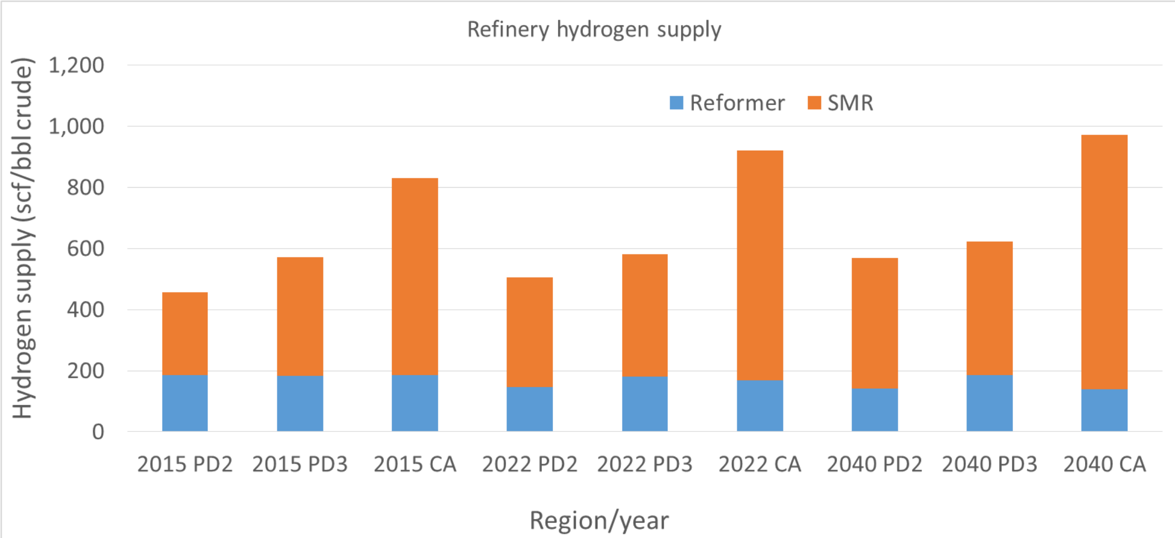


Figure 5-3. Hydrogen Supply in PADD/Region Base Case Refinery in 2015, 2022 and 2040

5.1.2 Aggregate LP Modeling Results of Refineries with E Set Fuels

The E set fuels produced in PADD 3 and CA in 2022 and 2040 are analyzed here. The modeling of E set fuels in PADD 2 was not carried out because it was observed from previous research that PADD 2 and PADD 3 have similar responses [5]. The refinery products associated with E set gasoline production are listed in Appendix 1, Tables A1-2–A1-5.

The RONs and MONs of the HOF gasoline resultant from LP modeling are compared to the measured values of the fuels that were used for engine tests, and are shown in the Figure 5-4 and Figure 5-5 for year 2022 and year 2040, respectively. It is worth mentioning that HOF gasoline includes two types of gasoline only: CG and RFG.

The measured properties are listed in Table 2-4, and the RON/MON values are again briefed below in Table 5-3.

Table 5-3. The Measured RON/MON Values of E Set HOF Gasolines

	F1	F7	F10	F14	F15	F16	F18	F19	F20
Measured RON	91.8	100.1	91.4	96.6	96.5	101.1	101.0	101.2	97.3
Measured MON	84.5	92.5	81.0	85.5	84.9	89.3	89.0	89.2	86.6

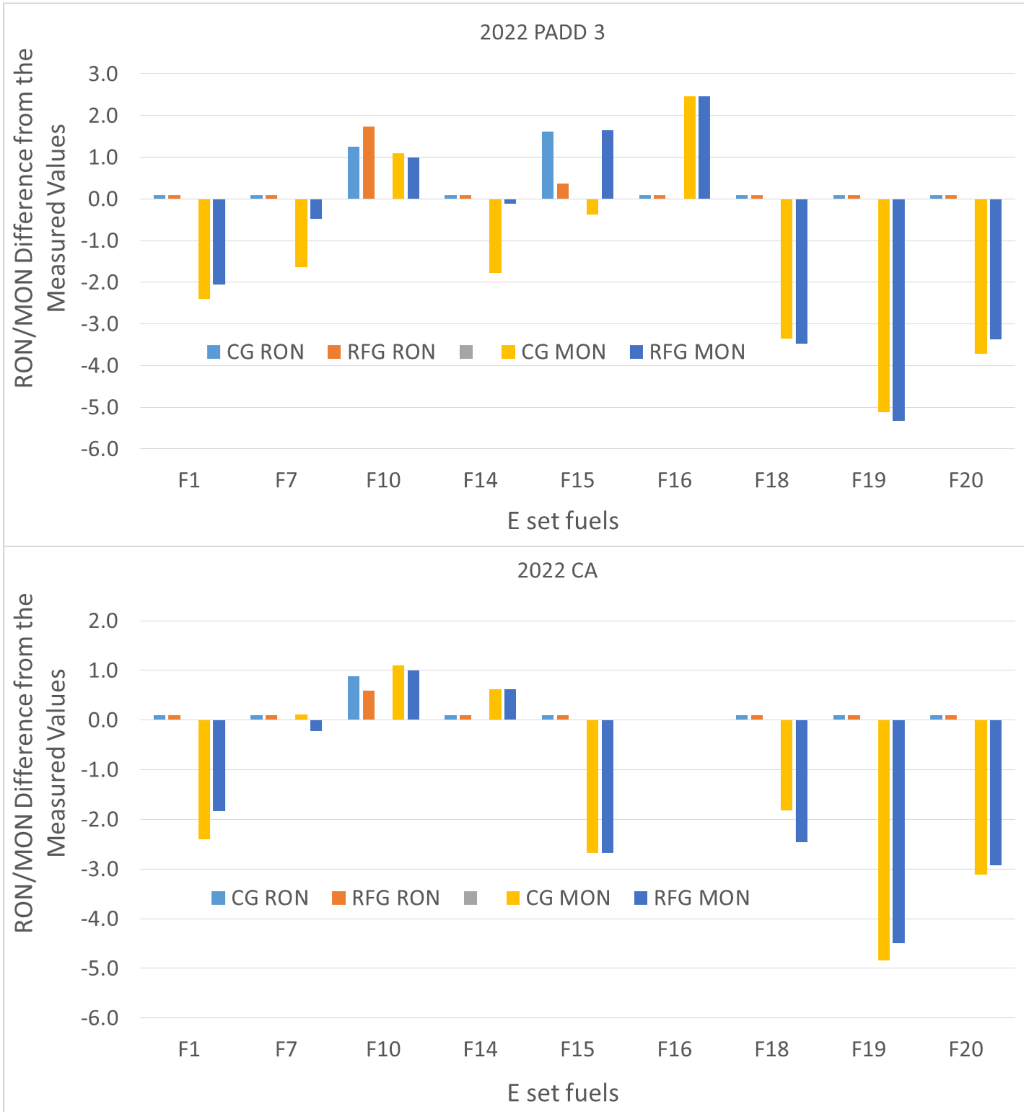


Figure 5-4. The Comparison of LP Modeling Resultant RONs and MONs of E Set HOF Gasolines Produced in PADD 3 and CA in 2022, with the Measured Values for RONs and MONs.

In 2022, for the E set HOF gasolines, the RONs from LP modeling match the measured RON values tightly for most cases, except for fuel F10 and F15 that show RON giveaways (gasolines are produced with higher RONs than required values). In contrast, the MONs from LP modeling show noticeable variations from the measured MON data (-4 to +3), as a result of LP modeling approach of floating MON. Nonetheless, all the LP modeling cases result in MONs greater than 82, as constrained by the model. Given the good match of RON values, the different LP modeling resultant MONs from the measured MONs indicate the divergence of the E set HOF gasoline OS from the targeted OS. However, this is expected to have a minor impact on WTW analyses, because the engine performance is mainly influenced by RON, while sensitivity has a secondary impact, as discussed in Section 3.

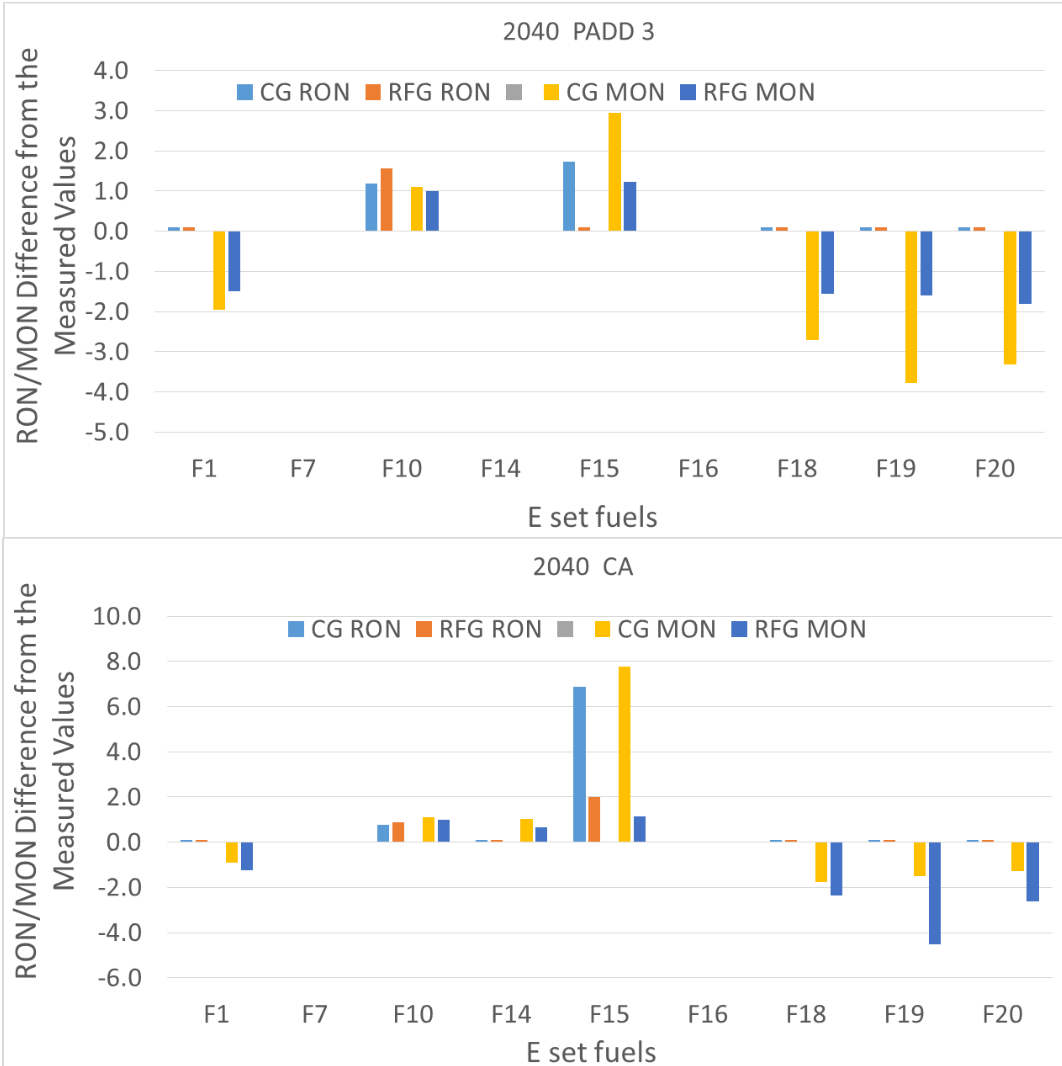


Figure 5-5. The Comparison of LP Modeling Resultant RONs and MONs of E Set HOF Gasolines Produced in PADD 3 and CA in 2040, with the Measured Values for RONs and MONs.

The results in 2040 are similar to those in 2022. LP modeling of F10 and F15 show RON giveaways. Especially, F15 HOF gasoline has much more RON giveaway in 2040 than in 2022, due to the large octane addition from HOF share of the domestic gasoline pool increase to 100% from 50%, with a high ethanol blending level of 30%, and only a mid–octane demand for the finished gasoline (RON 97–98). Whereas the LP modeling of F18, F19 and F20 results in lower MONs than the measured values of the fuels that are used for engine tests, indicating the HOF fuels produced from LP modeling have higher octane sensitivities than the fuels used for engine tests.

Overall, the different RONs and MONs of each E set HOF gasoline pool reflect the variations in gasoline pool components, and they are also strongly influenced and further complicated by the non-linear ethanol blending.

5.1.2.1 Aggregate Refinery Gasoline Export with E Set Fuels

The ratios of export gasoline/total gasoline with E set fuels production in each PADD refinery model results are displayed in Figure 5-6. The absence of a data point in the figure for a given fuel indicates that production of the fuel for that case was not feasible.

The ratio of export to domestic gasoline with the E set fuels produced in aggregate refineries is generally similar or higher than that that of base cases (designated by the dashed lines in the figure), except in PADD 3 for F7, F14, and F16 in 2022. That is, facing more challenges to produce these high-octane E set fuels, it is assumed that PADD 3 and CA refineries would divert more gasoline BOB to the exported gasoline pool, noting that exported gasoline does not contain ethanol. Similarly, the increased challenges of producing 100% HOF fuels in 2040, rather than the 50% share in 2022, led to significant increases in gasoline export in addition to an increased number of infeasible modeling cases. Figure 5-6 shows that there are sizeable gasoline exports (9–36 vol.% of total gasoline) associated with E set fuels production in PADD 3 and CA in year 2022 and 2040. It is worth mentioning that the base case exports in CA decrease from 2022 to 2040. It is because the G/D decreases and the CA Region goes to a strong diesel production mode. The gasoline exports decrease, however, at the same time there is an offsetting increase in diesel exports.

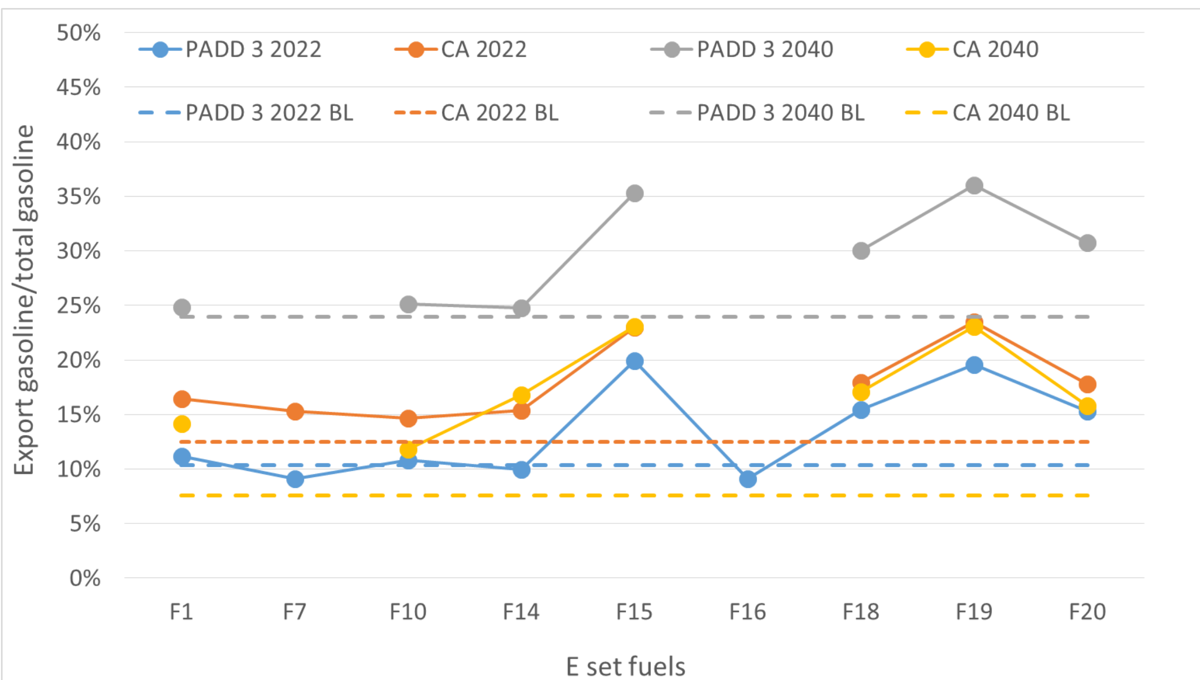


Figure 5-6. Export/Total Gasoline Ratios for Aggregate Refineries with E Set Fuel Production Compared to Base Case Baseline (BL) Values

5.1.2.2 Gasoline Components of Aggregate Refineries with E Set Fuel Production

The aggregate refinery products are summarized in Appendix 1 Tables A1-2 through A1-5. In order to comprehensively review gasoline production, the components of not only E set gasoline (BAU and HOF) but of the export gasoline produced in PADD 3 and CA in 2022 are analyzed and shown in Figure 5-7.

Figure 5-7 shows that the gasoline component shares differ among various E set gasoline types, and differ between the BAU gasoline, HOF gasoline, and export gasoline of each E set fuel.

Figure 5-7. The Components of E Set Fuels (BAU, HOF and Exported Gasoline) Produced in PADD 3 in 2022

For most E set fuels produced in PADD 3, BAU gasoline is dominated by reformates and FCC, while the HOF gasoline consists mainly of FCC and alkylates. In contrast, most of the export gasoline consists mainly of reformate and FCC. The challenging octane demand for Fuel 7 and Fuel 16 drives a maximized alkylate production/blending for HOF gasoline. The response of Fuel 14 gasoline production to high octane demand is also of interest, with more reformate being blended in the BAU pool and more alkylate being blended in HOF pool as a result of overall refinery optimization towards margin maximization. Fuel 15 has less alkylate in the HOF pool, and has a high volume share of naphtha. The "oversupply" of high octanes from 30% ethanol blending leads to the re-direction of reformate to the export pool.

For most E set fuels produced in CA, the BAU gasoline has lower shares of reformate and higher shares of alkylate than their PADD 3 counterparts (see Figure 5-8). Similarly, the HOF gasoline produced in CA has a smaller share of FCC and reformate, but a larger share of alkylate and naphtha than that produced in PADD 3. Interestingly, Fuel 7 (no FCC) and Fuel 14 (no naphtha) have very different distributions among blending components in PADD 3 and in CA.

It is also worth mentioning that the E set gasolines produced in PADD 3 have more C4 blended than that produced in CA, attesting to the more stringent RVP regulation in CA limiting the blending of lighter compounds (note the significantly higher share of RFG gasoline types in CA than in PADD 3—see Table 2-8).

A comparison of the components of the domestic and export gasoline pools for the E set fuels produced in PADD 3 and CA in 2040 is shown in Figures 5-9 and 5-10. In 2040, all the domestic gasoline produced is HOF gasoline. As in 2022, in 2040 the gasoline in CA hFas a lower share of reformate, FCC and C4s compared with the gasoline in PADD 3, but higher shares of alkylate and naphtha. Isomerate plays a minor role in the gasoline pool, and the share varies with fuel and PADD.

As in 2022, the PADD 3 E set domestic gasolines consist mainly of reformate, FCC and alkylates, while the export gasoline (without EtOH) is dominated by reformate, with the exception of Fuel 15 export gasoline, which has a large share of alkylate.

With the aromatic content constraint in CA, E set CA domestic gasoline is balanced among alkylate, reformate FCC, and naphtha, in addition to EtOH. Export gasoline is mostly reformate and isomerate.

5.1.2.3 Reformer Severity and Reformate Volume

Reformer operation severity and production volumes are listed in Table 5-4. As expected from the results in the base cases, for each E set fuel, the CA refinery would need to run its reformer with higher severity than that in baselines to boost octane production, though the CA reformer severities are lower in 2040 than 2022.

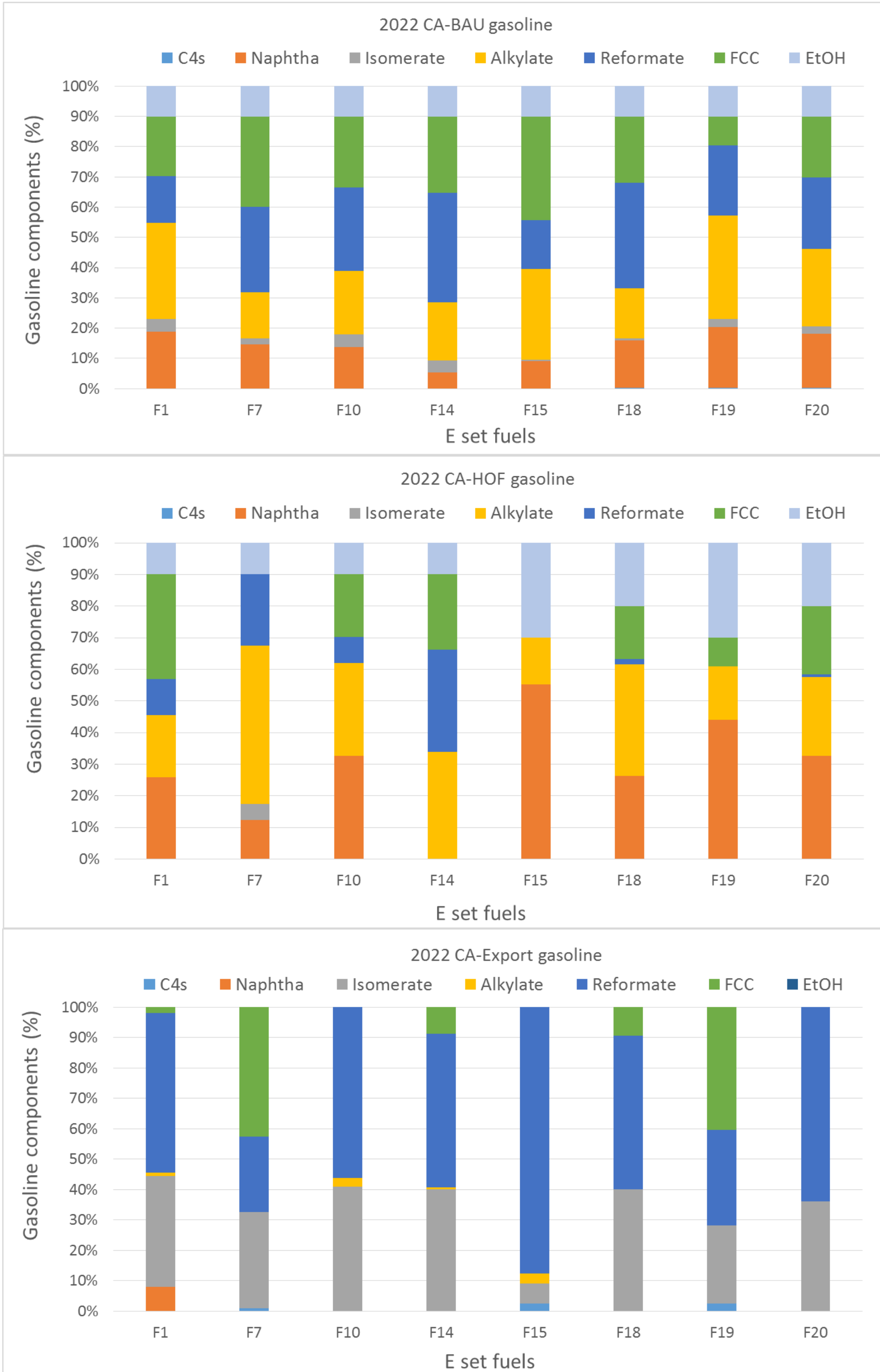


Figure 5-8. The Components of E Set Fuels (BAU, HOF and Exported Gasolines) Produced in CA in 2022

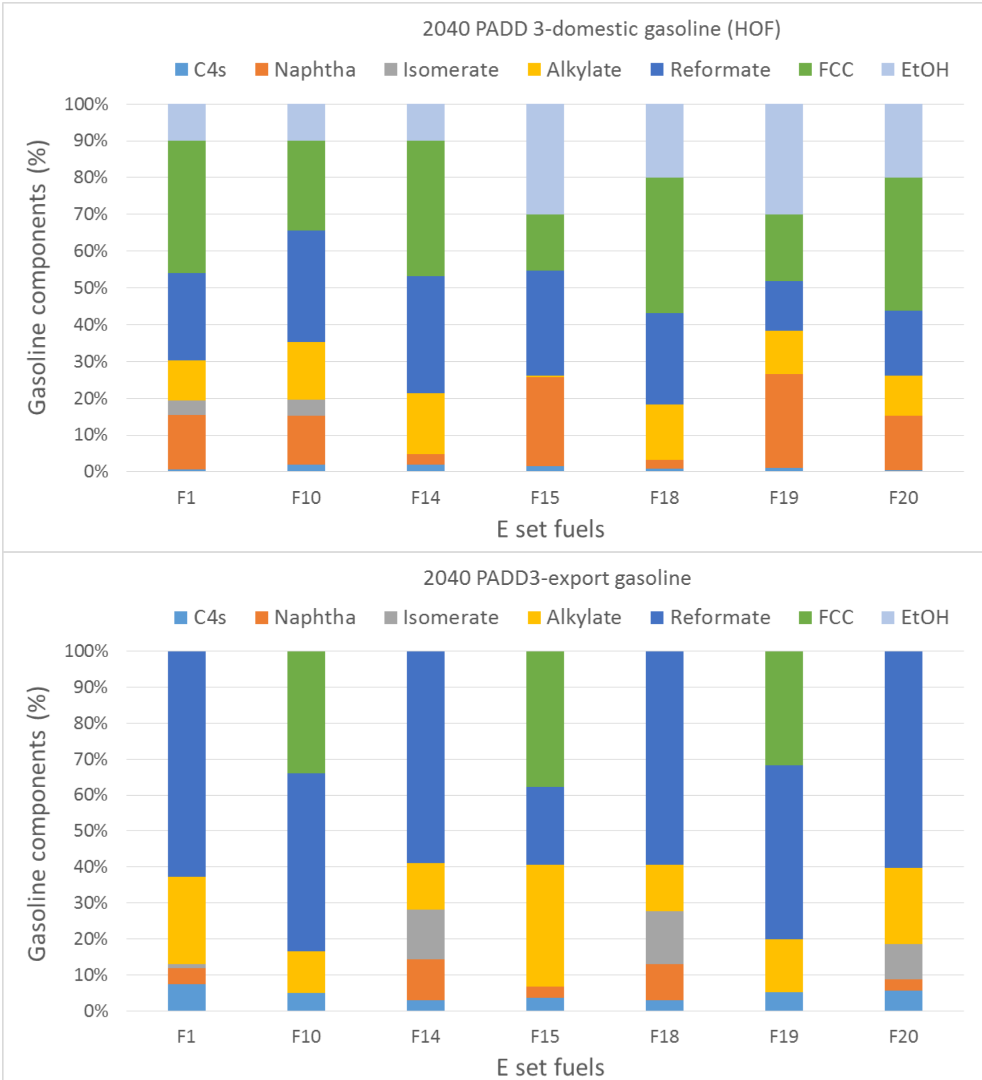


Figure 5-9. The Components of E Set Domestic Gasoline (HOF) and Export Gasoline Produced in PADD 3 in 2040

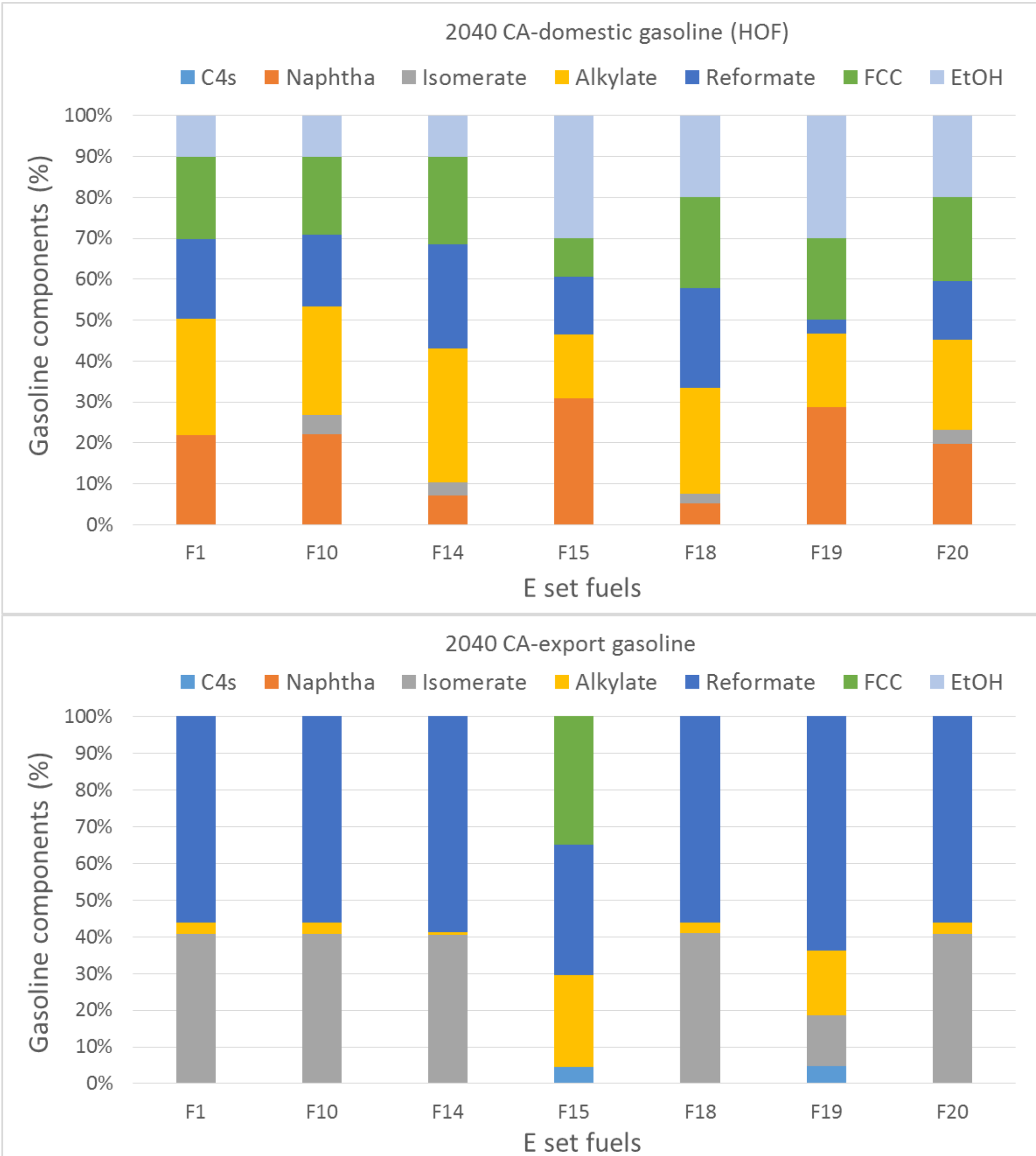


Figure 5-10. The Components of E Set Domestic Gasoline (HOF) and Export Gasoline Produced in CA in 2040

Table 5-4. Projected Reformer Severity and Production Volume of PADD 3 and CA Refineries with E Set Fuel Production in 2022 and 2040

Reformer	F1	F7	F10	F14	F15	F16	F18	F19	F20
PADD 3 2022									
Total Reforming capacity (BPD)	1,518,734	1,826,744	1,599,240	1,739,864	1,367,649	1,826,744	1,688,348	1,383,219	1,473,498
Avg Reforming Severity	90.0	97.0	90.3	91.6	90.0	99.5	90.9	90.0	90.0
Sev × BPD (in 1000)	136,686	177,131	144,393	159,359	123,088	181,707	153,482	124,490	132,615
CA 2022									
Total Reforming capacity (BPD)	231,487	318,933	259,266	311,510	190,208	--	282,451	173,452	217,676
Avg Reforming Severity	93.1	97.3	91.5	93.0	93.2	--	93.0	93.7	92.7
Sev × BPD (in 1000)	21,550	31,023	23,718	28,974	17,726	--	26,270	16,253	20,171
PADD 3 2040									
Total Reforming capacity (BPD)	1,602,574	--	1,688,839	1,898,020	1,452,504	--	1,843,048	1,466,371	1,602,119
Avg Reforming Severity	90.0	--	90.3	94.6	90.0	--	93.4	90.0	90.0
Sev × BPD (in 1000)	144,232	--	152,501	179,557	130,725	--	172,119	131,973	144,191
CA 2040									
Total Reforming capacity (BPD)	226,532	--	236,188	296,505	169,363	--	289,162	169,362	196,466
Avg Reforming Severity	91.2	--	91.1	94.7	90	--	91.9	90.0	91.5
Sev × BPD (in 1000)	20,656	--	21,525	28,078	15,243	--	26,560	15,243	17,984

Note: Dashes (--) denote infeasible cases.

The reformer severity of each refinery with E set fuels production in the two regions and two years are compared in Figure 5-11.

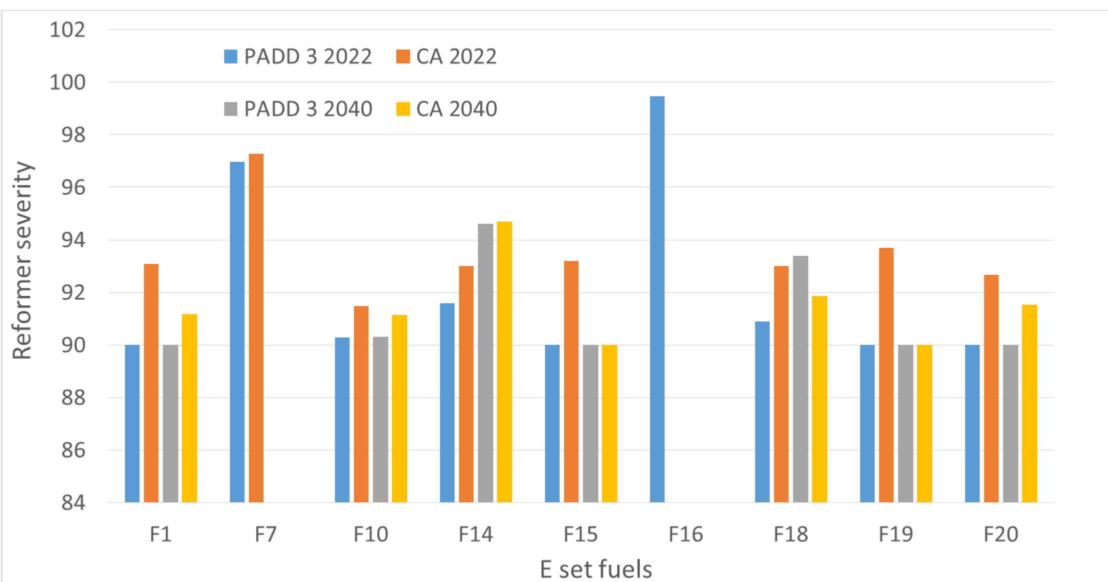


Figure 5-11. Reformer Severity of Each Aggregate Refinery with E Set Fuel Production in PADD 3 and CA in 2022 and 2040

The figure shows that the reformer severities decrease in CA from 2022 to 2040 for most E set fuels. It is because in some cases, there is a change in alkylate blendstock purchase which eases the high octane demand from reformer unit. Meanwhile it is also observed incremental diesel exports that may swing streams from gasoline to diesel than allows a reduction in severity as the refinery re-optimizes the octane balance.

5.1.2.4 Hydrogen Demand in Aggregate Refineries with E Set Fuel Production

The total hydrogen supply/demand of each refinery with E set fuels production in PADD 3 and CA refineries in 2022 and 2040 is shown in Figure 5-12.

For both PADD 3 and CA, the refinery hydrogen supply increases to meet demand from 2022 to 2040. The hydrogen supply from the reformer and SMR are compared and shown in Figure 5-13 and Figure 5-14.

From 2022 to 2040, the reformer hydrogen supply in PADD 3 increases, while the reformer hydrogen supply in CA decreases. This is consistent with the change in reformer contribution in each region (increase for PADD 3 and decrease for CA) from 2022 to 2040. For each fuel, the hydrogen supply in CA is much higher than that in PADD 3. The hydrogen supply from the reformer plays a lesser role than SMR does, and the differences between PADD 3 cases and CA cases are rather small. The additional hydrogen supplied by SMR in PADD 3 and CA refineries with E set fuels production are shown in Figure 5-14. The trends are similar to those of the total hydrogen supply.

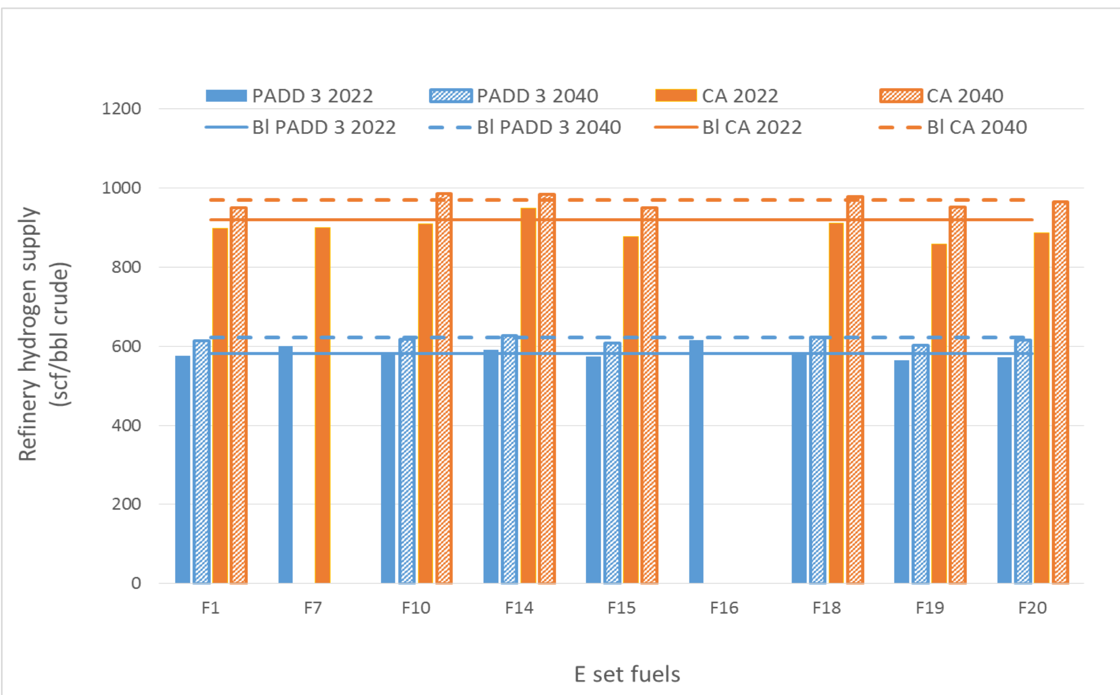


Figure 5-12. PADD 3 and CA Aggregate Refinery Hydrogen Demand with E Set Fuel Production in Year 2022 and 2040

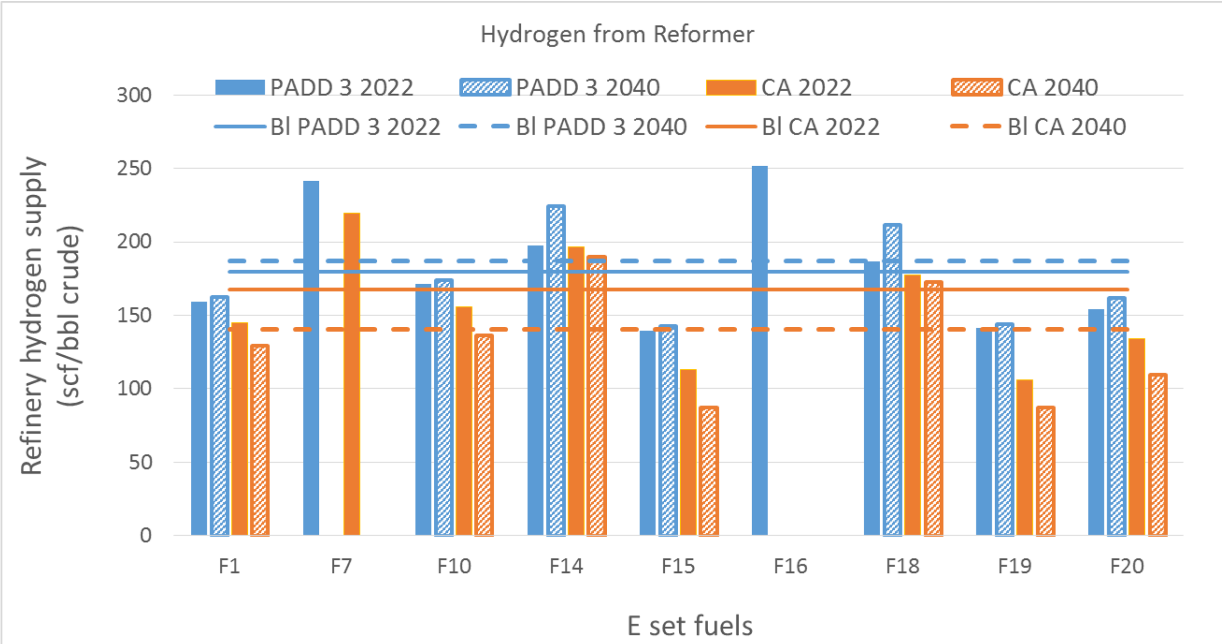


Figure 5-13. Projected Reformer Hydrogen Supply in PADD 3 and CA Aggregate Refineries with E Set Fuel Production in Year 2022 and 2040

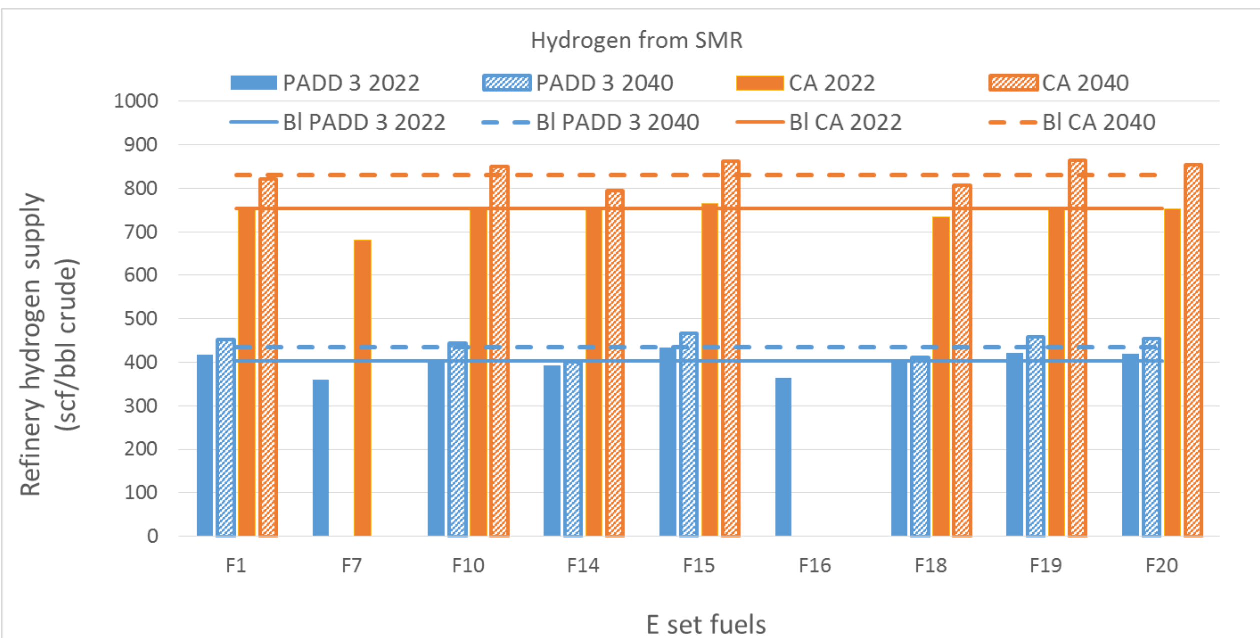


Figure 5-14. Projected SMR Hydrogen Supply in PADD 3 and CA Aggregate Refineries with E Set Fuel Production in Year 2022 and 2040

5.1.3 Configuration Refinery LP Modeling Base Case Results

Four configuration refinery models, CRK, LtCOK, HvyCOK and COKHCK, were developed to produce E set fuels in 2022 and 2040. The modeling results for operational feasibility are in Table 5-5. The production amount of refinery products are shown in Appendix 1 in Table A1-6.

Table 5-5. Summary of Configuration Refinery LP Modeling Feasible Solutions

	Configuration 2022				Configuration 2040			
	CRK	LTCOK	HVYCOK	COKHCK	CRK	LTCOK	HVYCOK	COKHCK
Base Cases	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible
F1 E10 Low RON	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
F7 E10 Hi RON	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
F10 E10 Low RON	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible
F14 E10 Mid RON	Feasible	Feasible	Feasible	Infeasible	Feasible	Feasible	Feasible	Infeasible
F15 E30 Mid RON	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
F16 E10 Hi RON	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
F18 E20 Hi RON	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible
F19 E30 Hi RON	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible
F20 E20 Mid RON	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible	Feasible

N/A: not applicable.

The base cases of the configuration refineries producing BAU gasolines were analyzed to serve as baselines for comparison with the E set fuels.

5.1.3.1 Gasoline Export in Configuration Refinery Base Cases

The export/total gasoline ratios for the configuration refinery base cases in 2022 and 2040 are about zero as it is assumed all the gasoline production to be domestic to avoid arbitrary allocation of gasoline streams to export market.

5.1.3.2 Configuration Refinery Base Case Gasoline Components

The components of the base case E10 gasolines produced in various configuration refineries are shown in Figure 5-15. With minimal gasoline exports in all the configuration refinery base cases, only the components of the pool of domestic gasolines (all BAU gasoline for base cases) are shown.

The pool of domestic gasolines produced from the relatively simple CRK and LtCOK configurations are dominated by reformate and FCC stream, while the domestic gasoline pools produced in the more complicated HvyCOK and COKHCK configurations are more balanced among various blending streams. HvyCOK has a noticeable higher naphtha blending share than the others, while COKHCK has a much higher alkylates share than the others.

Figure 5-15. Domestic Gasoline Pool Components for Configuration Refinery Base Cases in 2022 and 2040

The results for 2040 are very similar to those for 2022. The base case domestic gasoline pools are dominated by reformate and FCC for CRK, LtCOK, and HvyCOK and by a mixture of alkylate, reformatted and FCC for COKHCK. The makeup of the CRK, LtCOK, and HvyCOK base case domestic gasoline pools aren't too different from those of PADD 3 (see Figure 5-2). Similarly, the makeup of the base case domestic gasoline pool of the COKHCK isn't too different from that of the CA Regional base case.

5.1.3.3 Configuration Refinery Base Case Reformer Parameters

Given the importance of the reformer's flexibility in octane enhancement, its parameters are shown in Table 5-6.

Table 5-6. Reformer Operation Severity and Production Volume for Base Case Refineries with Four Configurations

Year	Unit Operations	CRK	LtCOK	HvyCOK	COKHCK
2022	Total Reforming Capacity (BPD)	36,748	31,955	29,604	20,404
	Avg Reforming Severity	90.0	90.0	90.9	93.5
	Sev × BPD (in 1000)	3,307	2,876	2,691	1,907
2040	Total Reforming Capacity (BPD)	37,241	33,547	28,704	22,767
	Avg Reforming Severity	90.0	90.0	91.9	90.0
	Sev × BPD (in 1000)	3,352	3,019	2,637	2,049

For both years, reformate volume decreases with the increasing complexity of the refinery, in the order CRK > LtCOK > HvyCOK > COKHCK. With similar reformer severity among these configurations, the reformer contribution (severity × BPD) also decreases with the increasing refinery complexity.

5.1.3.4 Configuration Refinery Base Case Hydrogen Supply

The refinery hydrogen supply for each configuration for both 2022 and 2040, determined by the demand, is shown in Figure 5-16.

Total hydrogen supply/demand depends on refinery configuration, increasing sharply for the more complex HvyCOK and COKHCK configurations. The CRK configuration refinery gets sufficient hydrogen supply from the reformer. Reformer-supplied hydrogen is similar for all four configurations, thus the high hydrogen demand in more complex refinery configurations will be supplied by a dedicated hydrogen production plant (SMR). There is slight increase in hydrogen supply/demand for all four configurations from 2022 to 2040.

5.1.4 Configuration LP Modeling E Set Fuel Results

Five fuels—F10, F14, F18, F19 and F20—were selected for study in configuration refineries cases. These fuels were chosen owing to their representative RON and ethanol blending level, and are expected to have higher potential for future prevalence in market. The feasibility of LP modeling of these cases was shown in Table 5-5 above. The products of the configuration refineries with E set fuels production are displayed are shown in Appendix 1 in Tables A1-7 through A1-14.

The RONs and MONs of HOF gasolines resultant from LP modeling are compared to the lab-measured values of the fuels that were lab-prepared and used for engine tests. The latter values are shown in the table below. It is worth mentioning that the lab measured RONs and MONs are only specific to fuels, while the LP modeling resultant RONs and MONs are specific to each modeling case, thus dependent on refinery configuration and year.

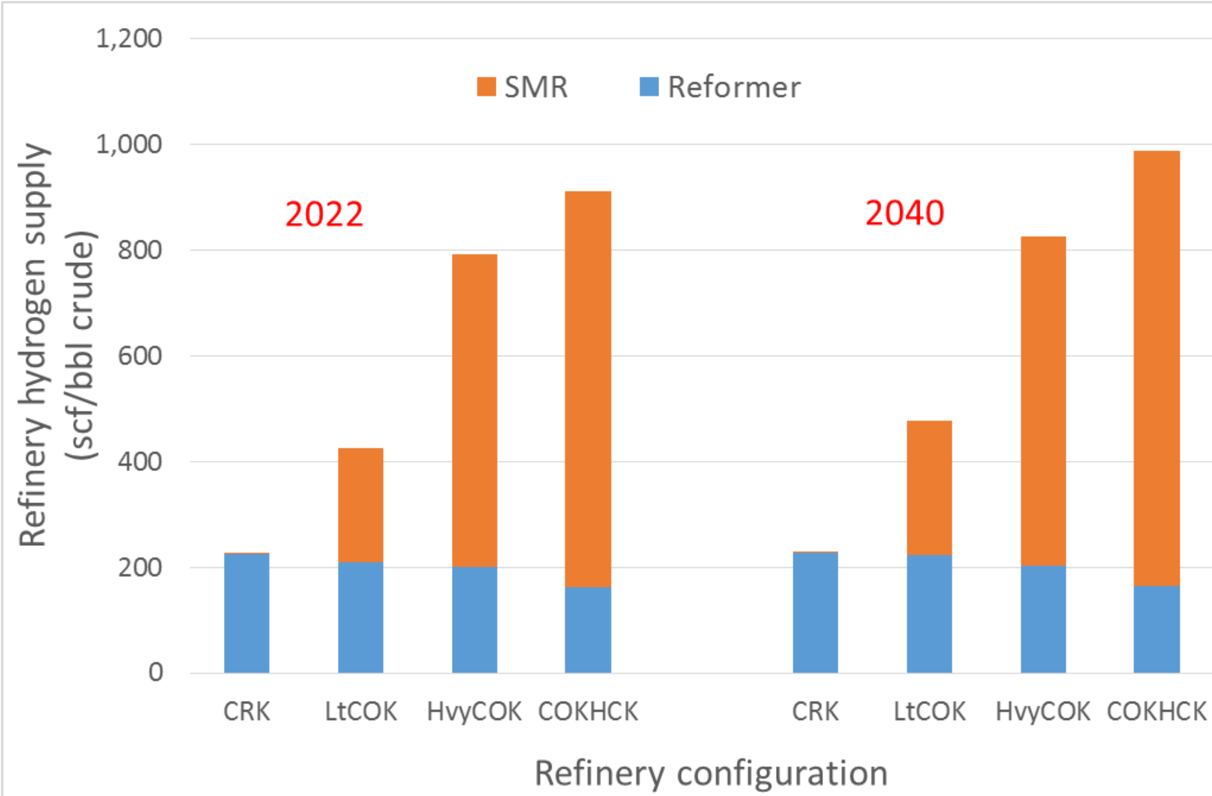


Figure 5-16. Configuration Refinery Hydrogen Supply for Base Cases

Table 5-7. The Lab-Measured RONs and MONs of E Set Fuels

Octane number	F10	F14	F18	F19	F20
Lab measured RON	91.4	96.6	101.0	101.2	97.3
Lab measured MON	81.0	85.5	89.0	89.2	86.6

The difference of LP modeling resultant E set HOF gasoline RONs and MONs from the lab–measured values are shown in Figure 5-17 and Figure 5-18 for year 2022 and 2040, respectively.

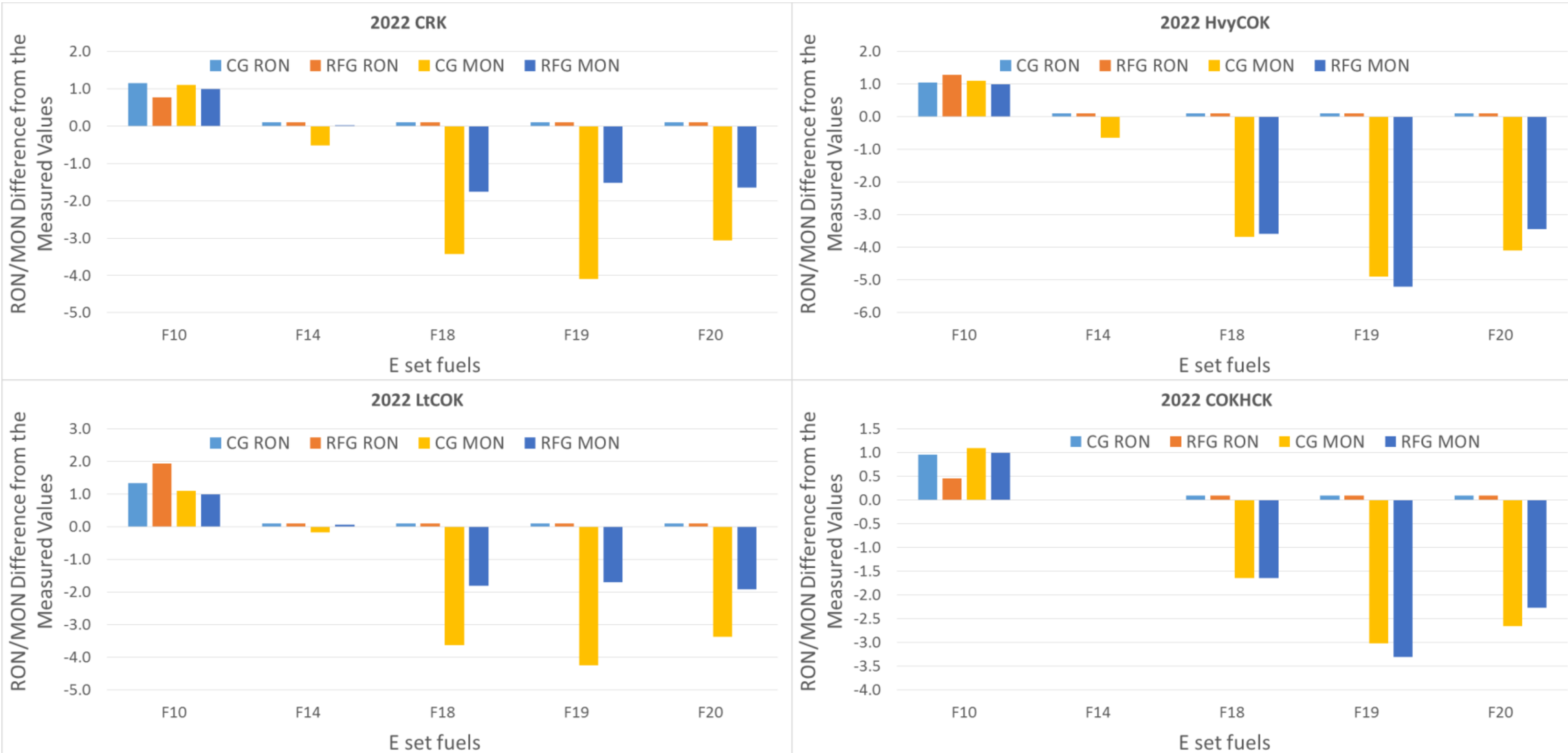


Figure 5-17. The Comparison of LP Modeling Resultant E Set HOF Gasoline RONs and MONs from the Lab–Measured Values, Produced in Various Configuration Refineries in 2022

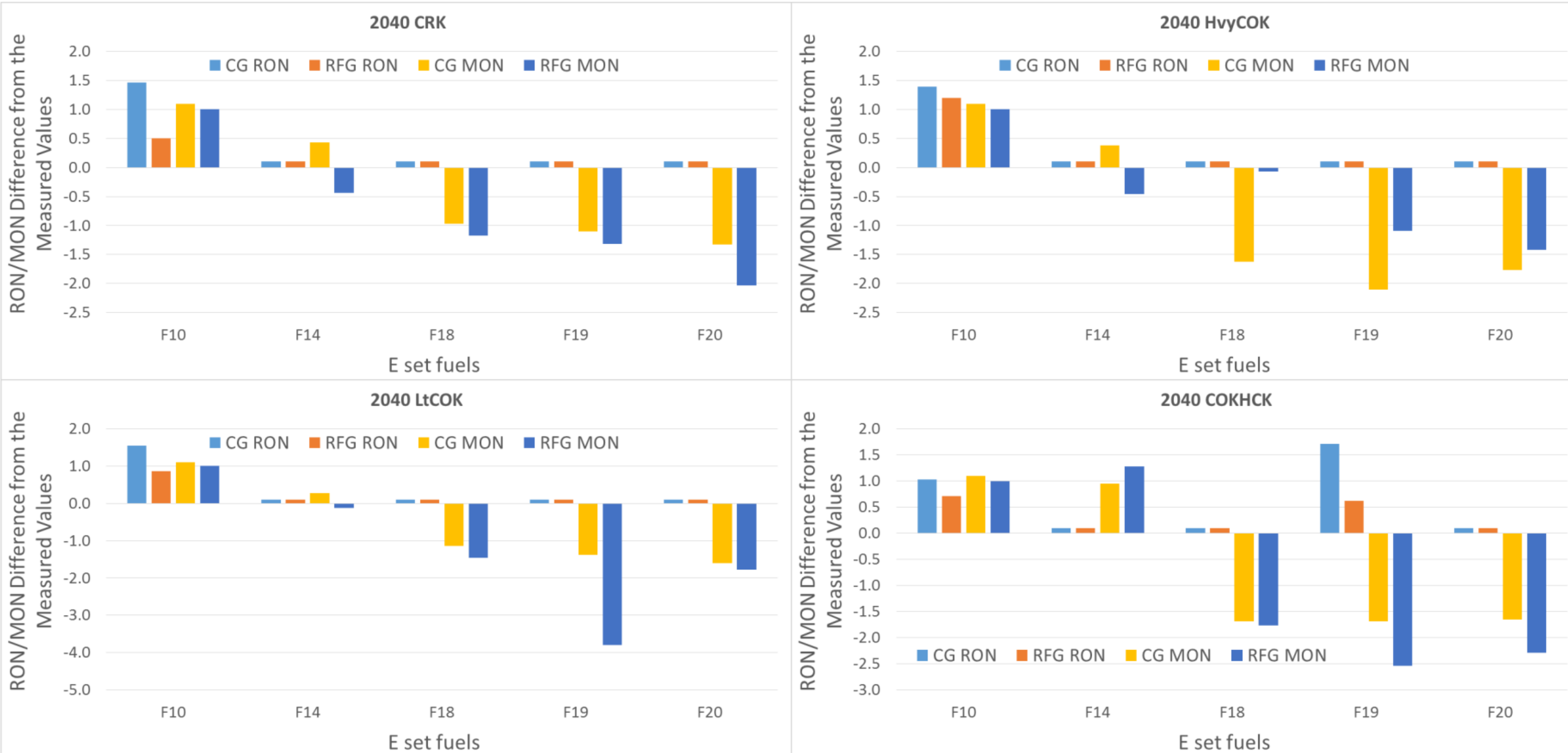


Figure 5-18. The Comparison of LP Modeling Resultant E Set HOF Gasoline RONs and MONs from the Lab–Measured Values, Produced in Various Configuration Refineries in 2040

In 2022, for the E set HOF gasolines, the RONs from LP modeling match the measured RON values tightly for most cases, except for fuel F10 which shows RON giveaways of about 1–2 number. Meanwhile, the MONs from LP modeling show noticeable variation from the measured MON data (-5 to +1.5), which is expected as LP modeling allows to float MON while constraining RON. Nonetheless, all the LP modeling cases result in MONs greater than 82, as constrained by the model.

In 2040, the divergence trends of E set HOF gasoline RONs and MONs from lab–measured values are similar with those in 2022 for CRK, LtCOK, and HvyCOK configurations cases, but different for COKHCK configuration refinery cases. For the latter configuration cases, the HOF gasolines of F14 and F19 show greater divergence in MON and RON, respectively. F14 HOF shows a MON giveaway of 0.9-1.3, and F19 HOF shows a RON giveaway of 0.6-1.7. The LP modeling resultant RONs generally match the lab-measured values well, some giveaways occur with high ethanol blending and/or with low octane demand for the finished gasoline.

5.1.4.1 Ratios of Export to Total Gasoline in Configuration Refineries with E Set Fuel Production

The ratios of export gasoline to total gasoline are shown in Table 5-8 below.

Table 5-8. The Ratios of Export/Total Gasoline in Configuration Refineries with E Set Fuel Production in 2022 and 2040

Year	Fuel	CRK	LtCOK	HvyCOK	COKHCK
2022	F10	0.01%	0.01%	0.01%	0.01%
	F14	0.01%	0.01%	0.01%	--
	F18	0.01%	0.01%	0.01%	1.55%
	F19	4.16%	3.57%	0.01%	2.51%
	F20	0.01%	0.01%	0.01%	0.22%
2040	F10	0.01%	0.01%	0.01%	0.01%
	F14	0.01%	0.01%	0.02%	--
	F18	0.02%	1.16%	0.02%	0.01%
	F19	0.02%	19.50%	15.66%	6.40%
	F20	0.02%	3.50%	0.02%	0.01%

5.1.4.2 The Components of Regular Gasoline Streams and HOF Gasoline Streams

In 2022, both BAU gasoline and HOF gasoline are produced in the configuration refinery (with 50 vol% share each). The higher octane number demand of HOF gasolines drives overall refinery re-optimization, resulting in different gasoline components for BAU and HOF gasoline. The E set gasoline components of BAU and HOF produced in various configurations in 2022 are shown in Figure 5-19 (the data are also shown in Appendix 2 table A2-1 through A2-4). The components of the export gasolines are not shown, as the export amounts are minimal or none for most cases.

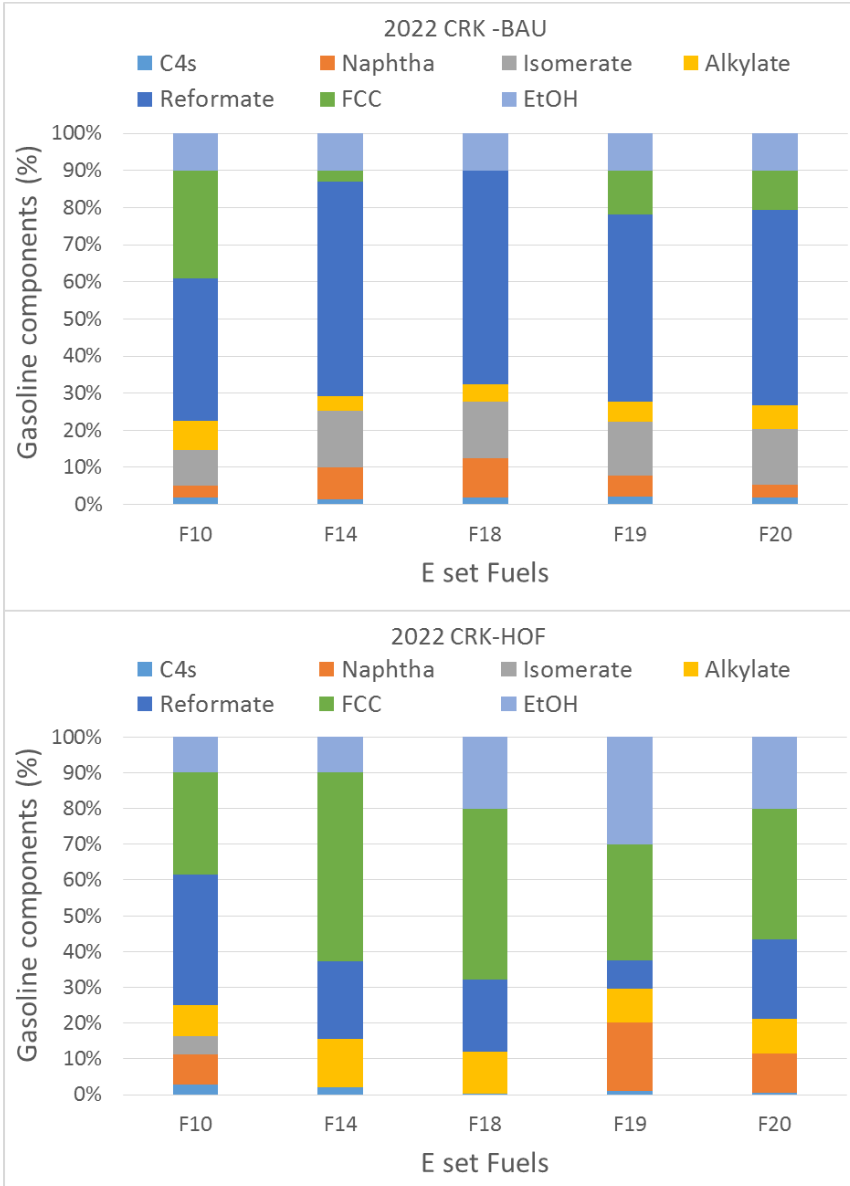


Figure 5-19. BAU and HOF Gasoline Components for E Set Fuels Produced in CRK Configuration in 2022

For Fuel 10, the component difference between BAU and HOF gasoline is minor, as the HOF gasoline specifications are very similar to those of BAU gasoline, as noted in the previous section. For all the other fuels with higher octane demands, the HOF gasolines have components significantly different from those of the BAU gasolines. The BAU gasolines consist mainly of reformate, and the HOF gasolines are dominated by FCC stream and have higher amounts of alkylates. Especially for Fuel 14 and Fuel 18, the demanding high octane target (RON 96 for Fuel 14 with 10 vol% EtOH and RON 101 for Fuel 18 with 20 vol%) requires more blending of high-octane alkylates. In contrast, the higher ethanol blending level in Fuel 19 (30 vol%) and Fuel 20 (20 vol% with 96 RON demand) introduces high octanes to the HOF pool, easing the refinery pressure to produce a high octane BOB stream, and thus allowing more blending of inexpensive, low-octane naphtha.

Compared to the BAU and HOF gasolines produced in the CRK configuration, the BAU gasoline produced in LtCOK configurations further increases FCC blending, and the HOF gasoline in LtCOK configurations further increases blending of FCC stream and alkylate stream. See Figure 5-20.

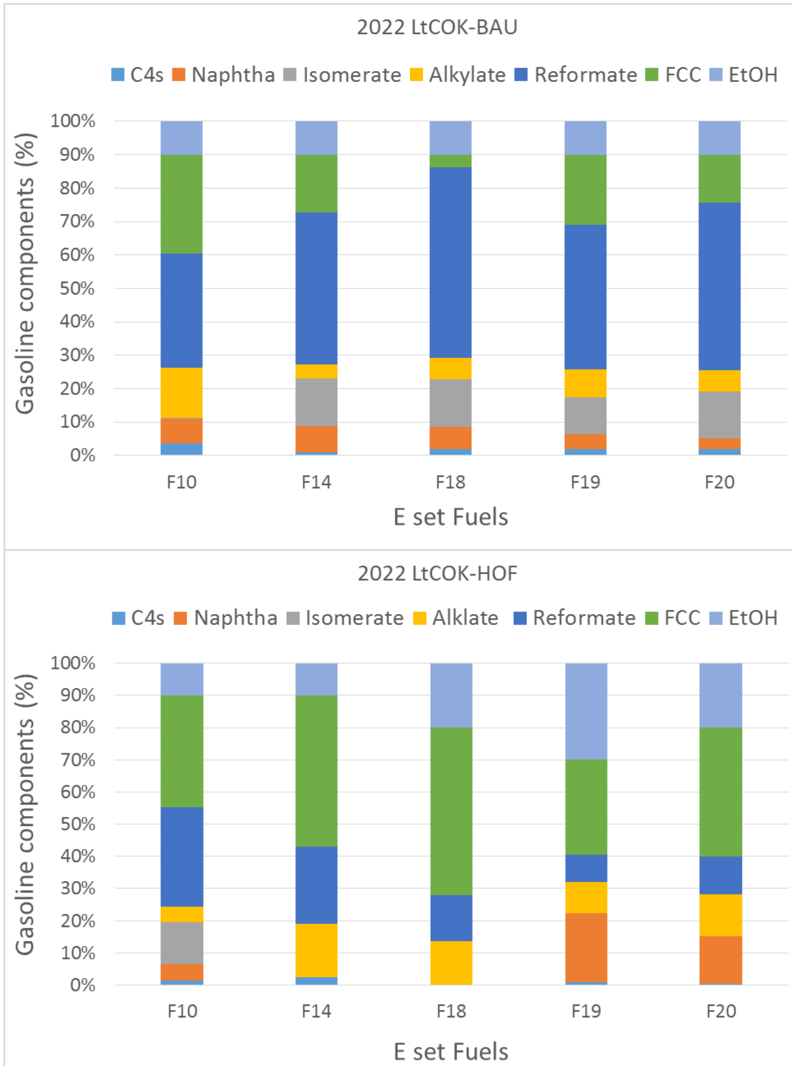


Figure 5-20. BAU and HOF Gasoline Components for the E Set Fuels Produced in LtCOK Configuration in 2022

Similar trends are observed for the E set fuels components modeled in the HvyCOK configuration, shown in Figure 5-21. It is worth noting that for BAU gasolines, the higher content of reformate is coupled with higher naphtha and/or isomerate content. Higher naptha and/or isomerate content is necessary because the high-boiling-temperature heavy reformate needs to be balanced with a lighter stream to enable the blended gasoline to meet distillation specifications.

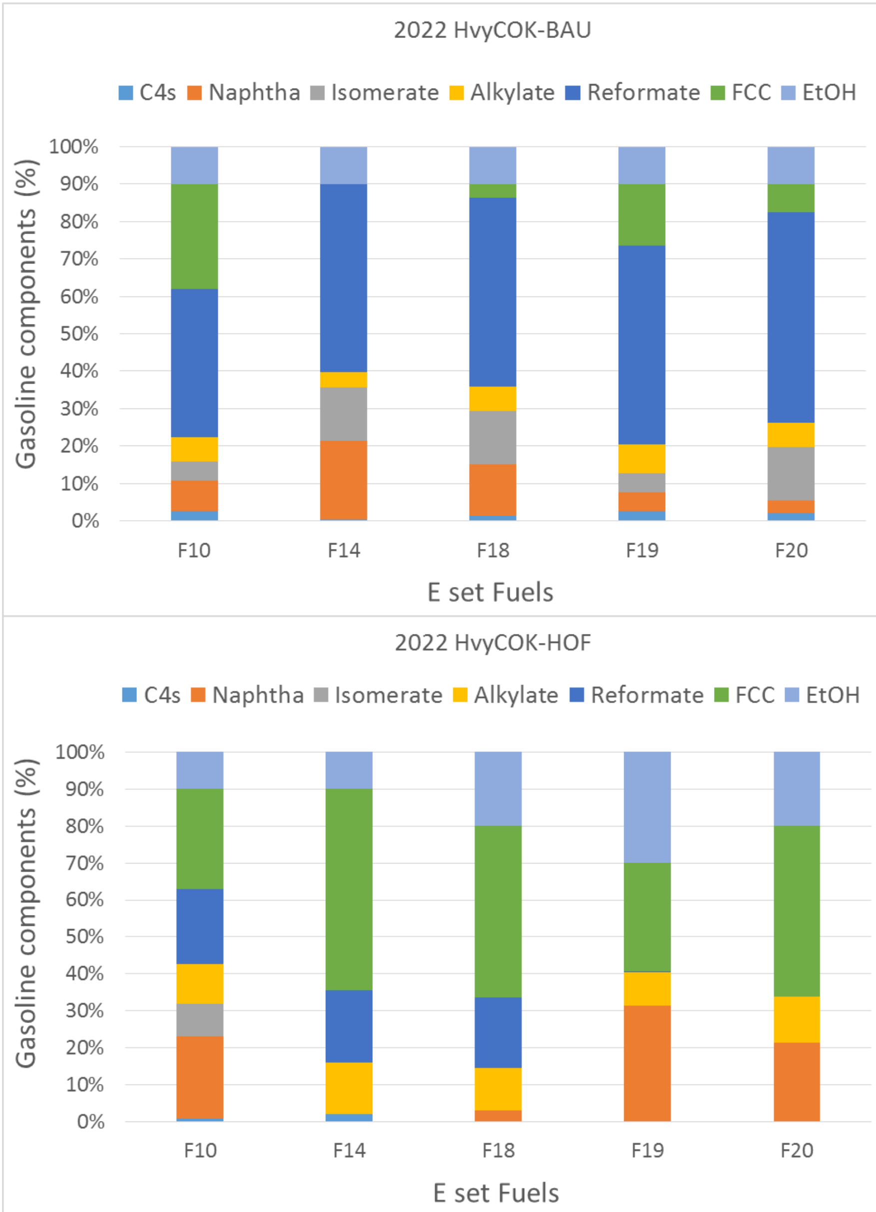


Figure 5-21. BAU and HOF Gasoline Components for E Set Fuels Produced in HvyCOK Configuration in 2022

For the COKHCK configuration in CA, modeling of Fuel 14 production did not yield feasible solutions, indicating a challenge of producing high-octane fuels with 10% EtOH blending with this configuration. The fuel components for the feasible cases are in Figure 5-22.

The components of the other fuels are different from those of their counterparts produced in other configurations, most notably in a much lower reformate share and much higher alkylate volume share. For CA, this results from the stringent gasoline specification on aromatic content, which limits the blending of aromatics and forces the high octane loss (of reformates) to be compensated for by the more blending of high-octane alkylates.

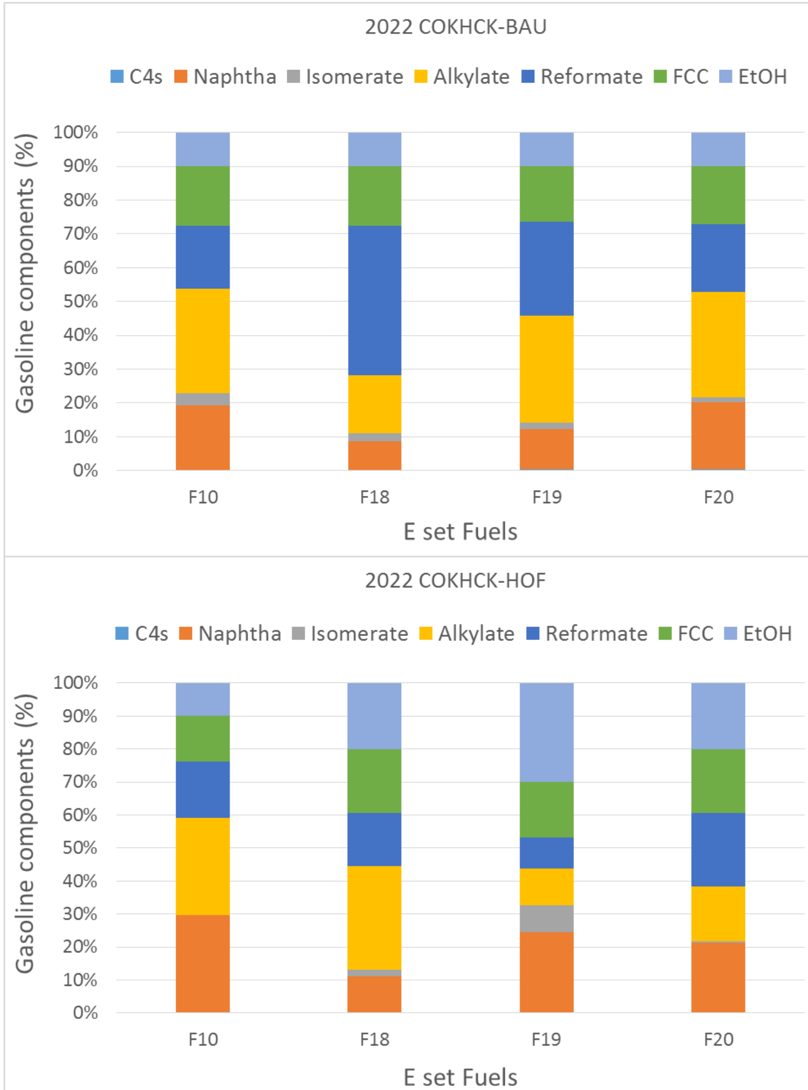


Figure 5-22. BAU and HOF Gasoline Components for the E Set Fuels Produced in COKHCK Configuration in 2022

The components of the E set fuels produced in the configuration refineries in 2022 are also listed in tables in Appendix 2 in Table A1-A4. The components of the E set fuels produced in the configuration refineries in 2040 are shown in Figure 5-23 to Figure 5-26 (data are shown in Appendix 2 Table A2-5).

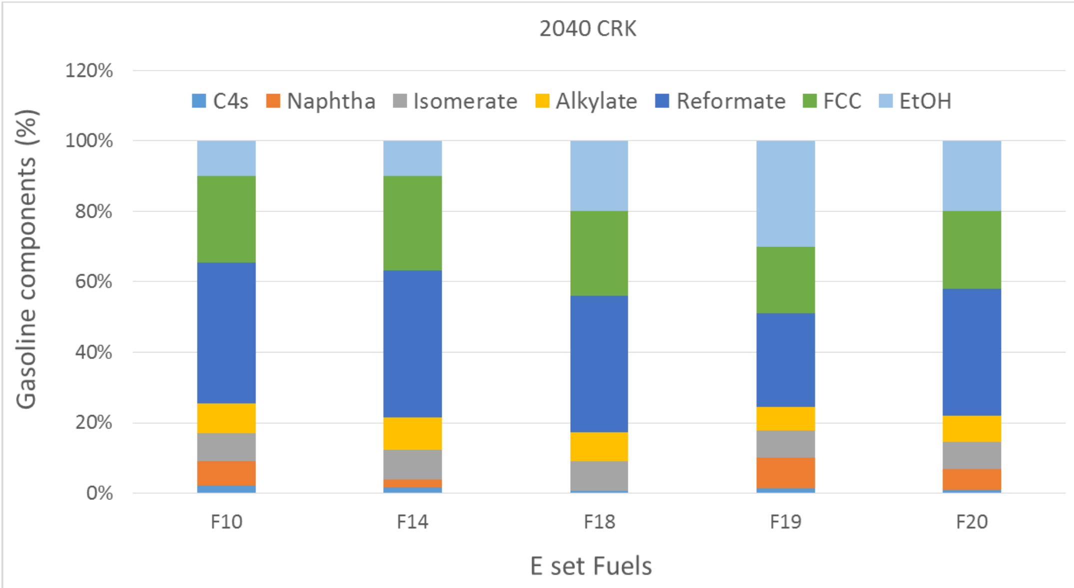


Figure 5-23. Components of the E Set Fuels Produced in CRK Configuration Refineries in 2040 (all HOF gasoline)

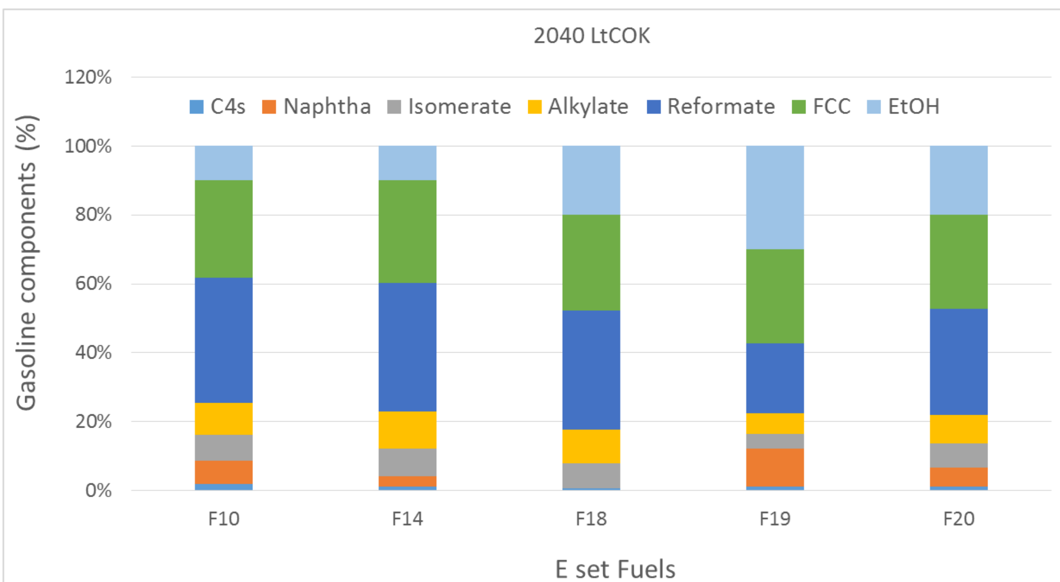


Figure 5-24. Components of the E Set Fuels Produced in LtCOK Configuration Refineries in 2040 (all HOF gasoline)

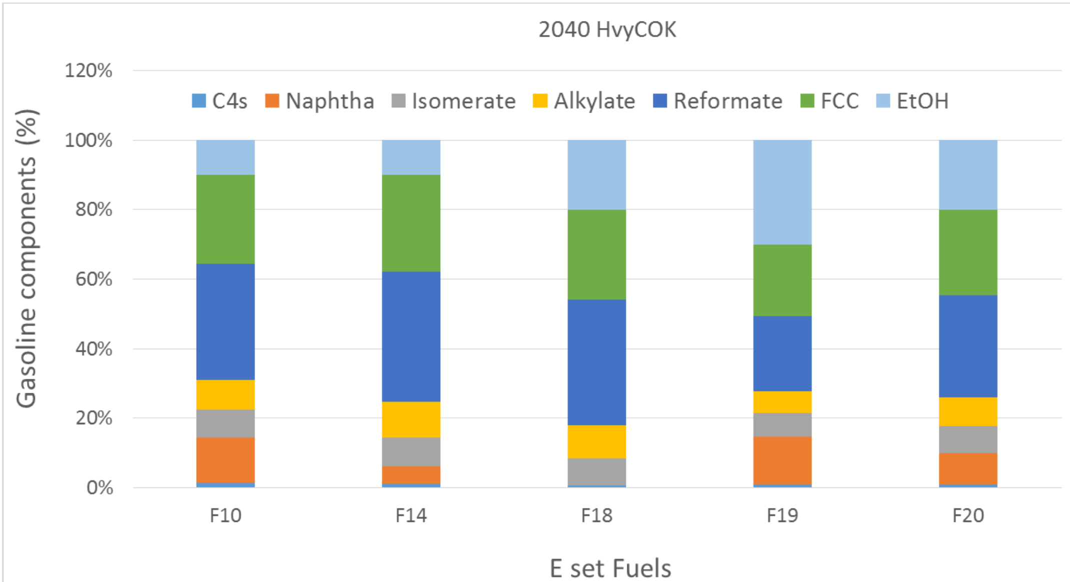


Figure 5-25. Components of the E Set Fuels Produced in HvyCOK Configuration Refineries in 2040 (all HOF gasoline)

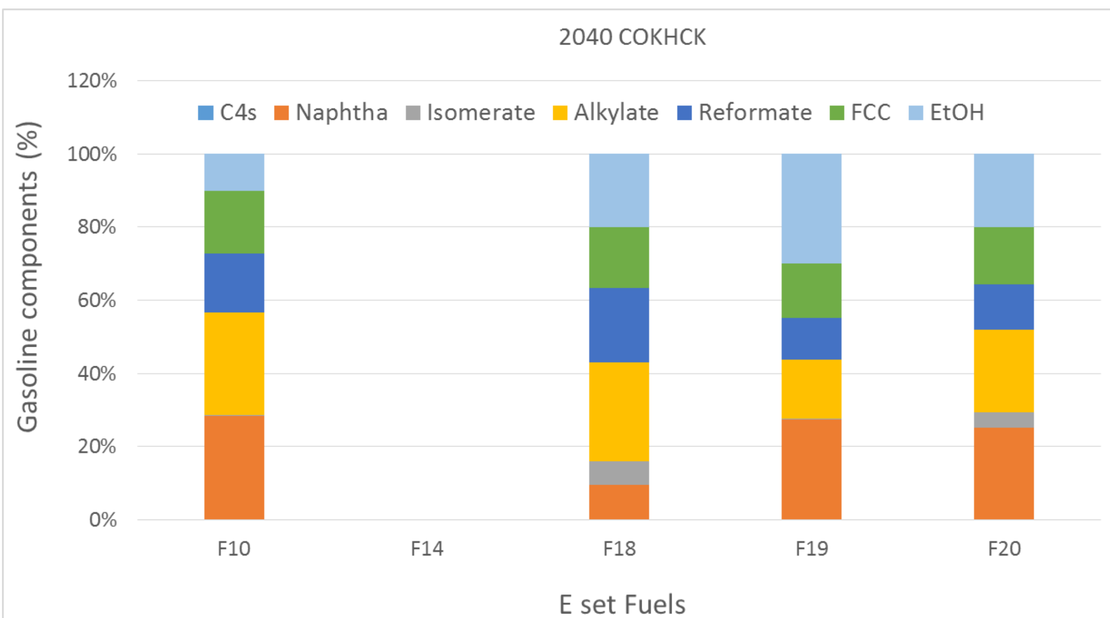


Figure 5-26. Components of the E Set Fuels Produced in COKHCK Configuration Refineries in 2040 (all HOF gasoline)

As was observed in the 2022 cases, the gasoline fuels produced in the configuration refineries in 2040 are dominated by reformate and FCC. In the COKHCK configuration relative to other configurations, for all fuels, the reformate and FCC content decreased and while the alkylate and naphtha content increased. This may occur because in order to increase alkylate yield, FCC operation severity is enhanced to yield more light olefins to feed the alkylation unit but less FCC gasoline.

5.1.4.3 The Reformer Severity and Reformate Volume of Each Configuration

The reformer severity and reformate production volume of various configuration refineries producing E set fuels are shown in Table 5-9.

Table 5-9. Reformer Severity and Reformate Volume of 2022 E Set Case Configuration Refinery

Reformate Severity	F10	F14	F18	F19	F20
CRK	90.0	94.0	93.5	92.1	90.0
LtCOK	90.0	93.9	90.9	90.0	90.0
HvyCOK	90.0	93.4	90.0	90.0	90.0
COKHCK	90.0	Not feasible	92.6	90.5	93.6
Reformate volume (BPD)	F10	F14	F18	F19	F20
CRK	35,856	37,228	36,541	30,727	35,102
LtCOK	32,041	33,164	33,887	26,874	29,297
HvyCOK	29,513	33,223	32,902	22,508	23,609
COKHCK	20,209	Not feasible	27,420	13,923	19,665
Reformate volume × severity (thousand BPD)	F10	F14	F18	F19	F20
CRK	3227	3498	3415	2830	3159
LtCOK	2884	3114	3082	2419	2637
HvyCOK	2656	3105	2961	2026	2125
COKHCK	1819	0	2539	1260	1840

For Fuel 10, the reformer severity does not change with the configuration, but for the other fuels, the severity varies with the configuration. In particular, higher severity is observed for Fuel 14 in all configurations where it is feasible in response to Fuel 14's high octane target (without additional high-octane ethanol blending). For each E set fuel, the reformate production volume decreases in the order: CRK > LtCOK> HvyCOK>COKHCK configurations, in that order, consistent with the component share decrease that accompanies increasing refinery complexity, as described in the previous section. As mentioned earlier, higher severity reformer operation is coupled with a lower yield, so it is useful to evaluate the overall reformate contribution by multiplying reformer volume by severity. For each fuel, the reformate contribution decreases with the increase of refinery complexity, reflecting the more diversified gasoline blending sources and increased flexibilities in the more sophisticated refinery configuration.

The reformer severity in configuration refineries with E set fuels production in 2040 is shown in Figure 5-27, with the severity for 2022 also shown for comparison.

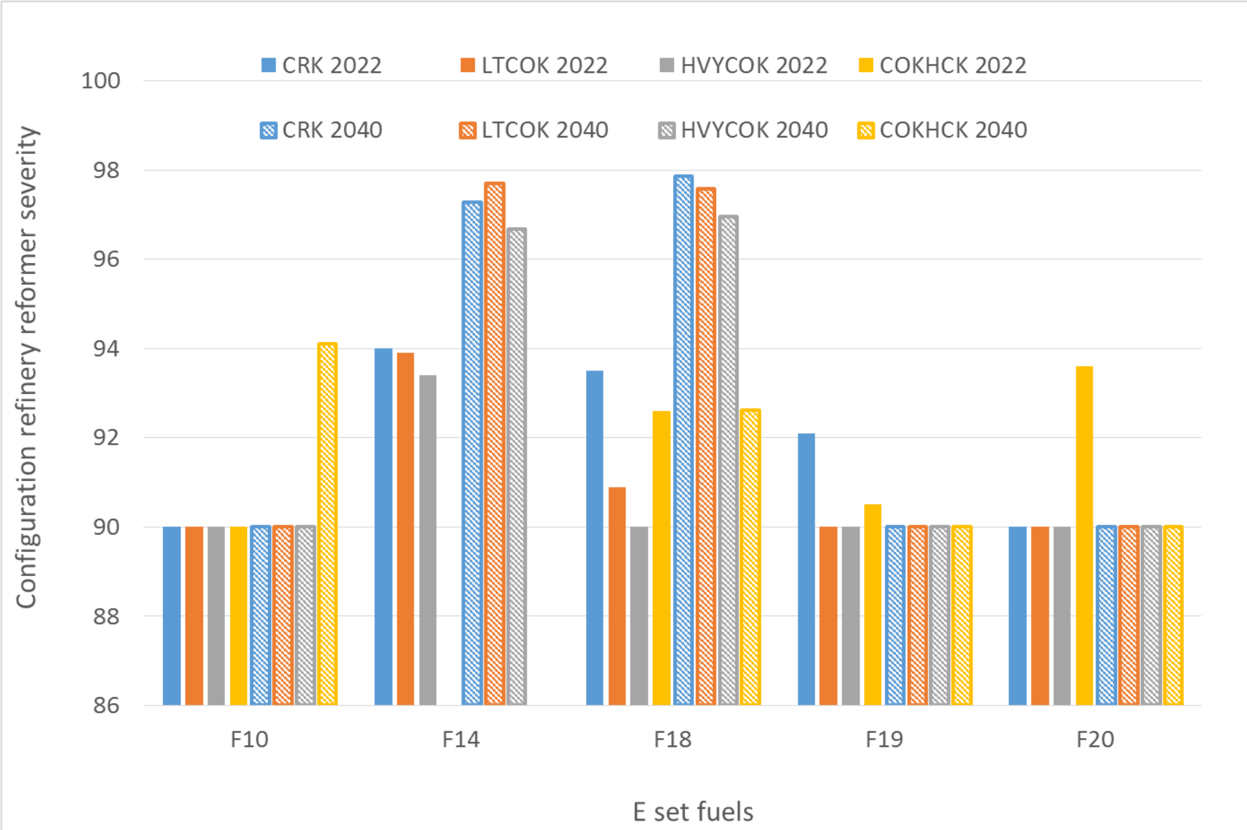


Figure 5-27. Reformer Severity of Configuration Refineries with E Set Fuel Production in 2040

The configuration refinery with 100% E set HOF fuel production shows changes in reformer severity from 2022 to 2040 for different fuels produced in different configurations. The increased severity for Fuel 10 production in COKHCK, Fuel 14 (in all configurations) and Fuel 18 (in all configurations) reflects the challenges refineries face in meeting the high octane target. In contrast, the relatively low and flat severity for Fuel 19 (in all configurations) and Fuel 20 (in all configurations) reflects the ease with which these refineries can produce high octane gasolines when high level of EtOH are blended into the gasoline pool.

Reformate volume is listed in Table 5-10, showing that reformate volume decreases with increasing refinery complexity.

Table 5-10. The Reformate Volume Produced in the Configuration Refineries with E Set Fuel Production in 2040

Reformate Volume (bbl/day)	CRK	LTCOK	HVYCOK	COKHCK
F10	35528	31697	27995	16460
F14	37347	33877	32107	--
F18	34835	33922	30834	21857
F19	24038	27936	22843	14776
F20	32265	29627	25316	12501

The reformate contribution to the gasoline pool in 2040 is shown in Figure 5-28, with the results from 2022 shown for comparison. From 2022 to 2040, the overall contribution of reformate to the gasoline pool responded to the increased demand for high octane differently, depending on both the fuel and the configuration.

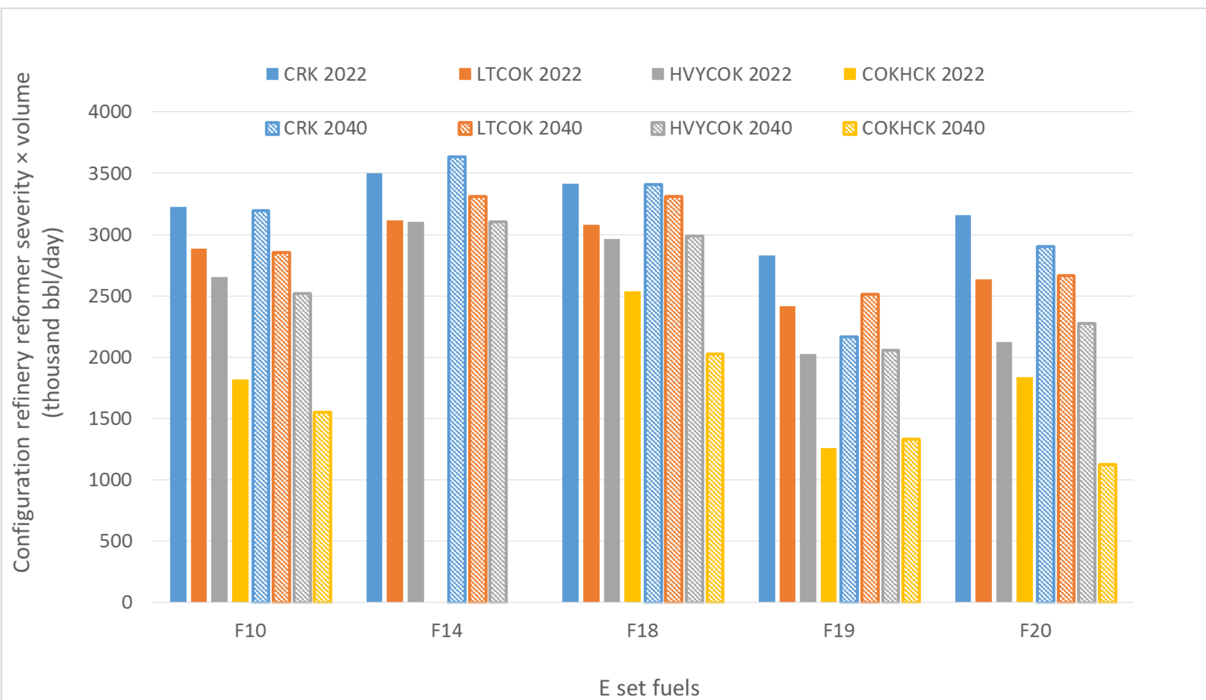


Figure 5-28. Reformate Contribution for E Set Gasolines Produced in Configuration Refineries in 2022 and 2040

5.1.4.4 Hydrogen Usage in Each Configuration

Hydrogen demand for each refinery depends on crude slate, refinery complexity, product slate, refinery operation, and so on. Hydrogen production in 2022 and 2040 for each refinery configuration producing E set fuels is shown in Tables 5-11 and 5-12, respectively.

Table 5-11. 2022 Hydrogen Production in Each Refinery Configuration with the Production of E Set Fuels

2022	Source	CRK (scf/bbl)	LTCOK (scf/bbl)	HVYCOK (scf/bbl)	COKHCK (scf/bbl)
F10	Reformer	217.2	208.0	193.2	140.8
	SMR	0.0	220.4	595.5	778.2
F14	Reformer	259.2	248.5	248.5	--
	SMR	0.0	200.9	573.5	--
F18	Reformer	249.0	232.5	222.9	220.3
	SMR	0.0	233.8	613.9	713.9
F19	Reformer	190.6	167.5	138.8	94.4
	SMR	8.4	273.2	646.0	796.8
F20	Reformer	211.0	187.5	147.5	156.2
	SMR	0.0	263.4	620.2	741.6

Table 5-12. 2040 Hydrogen Production in Each Refinery Configuration with the Production of E Set Fuels

2040	Source	CRK (scf/bbl)	LTCOK (scf/bbl)	HVYCOK (scf/bbl)	COKHCK (scf/bbl)
F10	Reformer	214.3	207.0	183.9	129.6
	SMR	0.0	263.3	636.8	834.1
F14	Reformer	286.3	283.1	264.6	--
	SMR	0.0	192.4	557.5	--
F18	Reformer	288.3	283.1	254.7	175.7
	SMR	0.0	194.0	552.3	800.7
F19	Reformer	176.0	175.9	141.3	98.2
	SMR	16.6	279.6	640.6	848.2
F20	Reformer	212.6	189.9	161.8	83.1
	SMR	0.0	274.7	630.8	876.6

For both 2022 and 2040, the hydrogen supply responds to hydrogen demand increases with the refinery's increasing complexity, which is in turn related to crude quality (API and sulfur). The COKHCK configuration (California) demands the most hydrogen. This is most likely for one or both of two reasons: First, CA refineries use very heavy crudes (low API), requiring hydrogen's aid to convert heavy crudes to valuable lighter fuels (gasoline, diesel, etc.). Second, many CA refineries include hydrocrackers, which require hydrogen. See Figure 5-29.

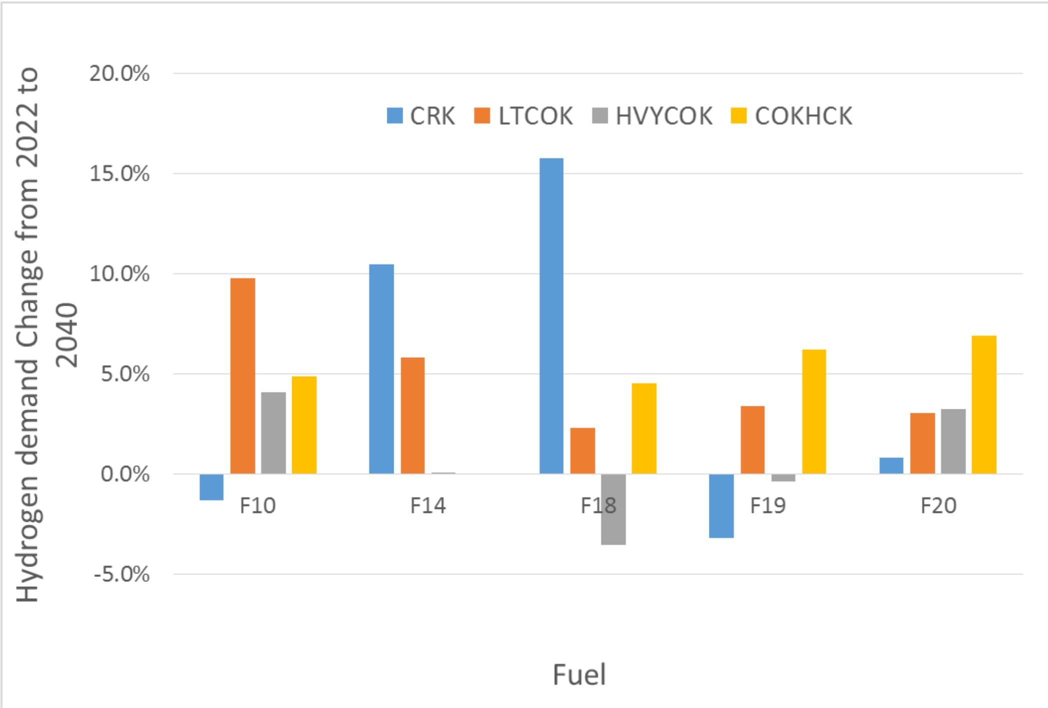


Figure 5-29. The Change in Total Hydrogen Demand for Four Configuration Refineries from 2022 to 2040

In most cases, hydrogen demand in configuration refineries increased from 2022 to 2040 as the HOF gasoline share increased from 50 vol% to 100 vol%.

5.2 LP Modeling Results of BR Set Fuels

5.2.1 LP Modeling Results of BR Fuels in Aggregate Refineries

Table 5-13 shows the cases with feasible solutions from LP modeling of the PADD/Regional refineries with BR fuels production. As noted earlier, the LP modeling included the constraint that additional capital investment in refinery operations was not allowed. Additional refinery capital investment may allow infeasible solutions to be come feasible. However, this was not specifically investigated in the present study. As stated earlier, Appendix 5 summarizes some capital expansion studies for the E set fuels (F14 and F18) that have high potential of market prevalence, to examine the alternative processes of these gasoline BOB production for potential economic or environmental benefits.

Table 5-13. Summary of LP Modeling Feasible Solutions for Aggregate Refineries with BR Fuel Production

Year	Regional 2022			Regional 2040		
Region	PADD 2	PADD 3	CA	PADD 2	PADD 3	CA
Fuel BR1 Mid Ron	Feasible w/TOL	Feasible	Infeasible	Infeasible	Infeasible	Infeasible
Fuel BR2 Mid RON	Feasible	Feasible	Infeasible	Feasible	Feasible	Infeasible
Fuel BR3 Hi RON	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
Fuel BR4 Hi RON	Feasible w/TOL	Feasible w/ TOL	Infeasible	Feasible w/TOL	Feasible w/TOL	Infeasible

TOL: toluene

Overall, the production of high-RON BR fuels is challenging. No LP model in CA yields feasible solutions, so LP simulations of the BR set fuels produced in aggregate refineries will focus on PADD 2 and PADD 3. The BR fuel cases differ from the base case and E set fuels by blending bioreformate instead of bio-ethanol.

Although the BR blendstock (almost entirely aromatics straddling the C7-C11 range) has high octane numbers, it has the drawback of a high boiling point, which limits its blending shares by causing it to hit the T90 specification. To decouple the bioreformate's benefits from its drawbacks, we tested the approach of splitting it into low-boiling and high-boiling streams. However, this approach would require some modification to refineries and their modeling (e.g., to distillate BR stream), which is time-consuming and introduces additional factors such as the cut point of the BR stream. With limited resources, rather than trying to determine the optimal cut point of the bioreformate blendstock, we decided to use "purchased" bio-toluene (assuming the BR stream has been pre-split into toluene and a heavier stream) as a surrogate to test this approach without any refinery unit modification. This approach turned out to be fruitful, solving several more cases which would have been infeasible otherwise. It is worth noting that the "bio-toluene" is set to have the same price as the BR stream, as the present study objective was not about refineries economic with various bio-blendstocks.

Using toluene as a surrogate for bioreformate enables the feasibility of LP modeling of several BR set fuels. However, the production process of bio-toluene might consume more energy than the production process of bioreformate since a separation process is needed to separate toluene from the rest of bioreformate. Of course, using bio-toluene as a surrogate for bioreformate might impact the economics of the bioreformate production process, not only by increasing energy use, but also likely impacting the economic values of the remaining bioreformate after bio-toluene extraction. This economic discussion is beyond the scope of current study, which focuses on the impact of blending bioreformate/bio-toluene in gasoline on GHG emissions. The impact of separating bio-toluene from bio-reformate could be addressed in the future if the information regarding separation is available.

The RONs and MONs of BR set HOF gasolines resultant from LP modeling are compared to the lab–measured values of fuels that are used for engine tests. The lab–measured values are shown in the Table 5-14 below and the comparison results are shown in the figure below.

Table 5-14. The Lab–measured RONs and MONs of BR Set HOF Gasolines

Year	2022						2040			
PADD	PADD 2			PADD 3			PADD 2		PADD 3	
BR HOF gasoline	BR1-T	BR2	BR4-T	BR1-T	BR2	BR4-T	BR2	BR4-T	BR2	BR4-T
LAB HOF RON	97.6	97.3	101.0	97.6	97.3	101.0	97.3	101.0	97.3	101.0
LAB HOF MON	87.2	87.0	90.3	87.2	87.0	90.3	87.0	90.3	87.0	90.3

It is worth mentioning that for HOF gasolines the lab measured RON and MON values do not vary with refinery or year, but the modeled results do.

In both year 2022 and 2040, the RONs from LP modeling match the measured RON values well for all the BR/BR-T cases, produced in both PADD 2 and PADD 3 aggregate refineries. In contrast, all the MONs vary with fuel, refinery and year, within the range of -1.5 to +2.5 (shown in Figure 5-30). Most BR set HOF gasolines have higher MONs than the measured values, indicating lower OS than that of the fuels used for engine tests. This is different from the E set fuels cases modeled in aggregate refineries, in which most E set HOF gasolines show lower MONs than the measured values, indicating higher OS than that of the lab-made fuels.

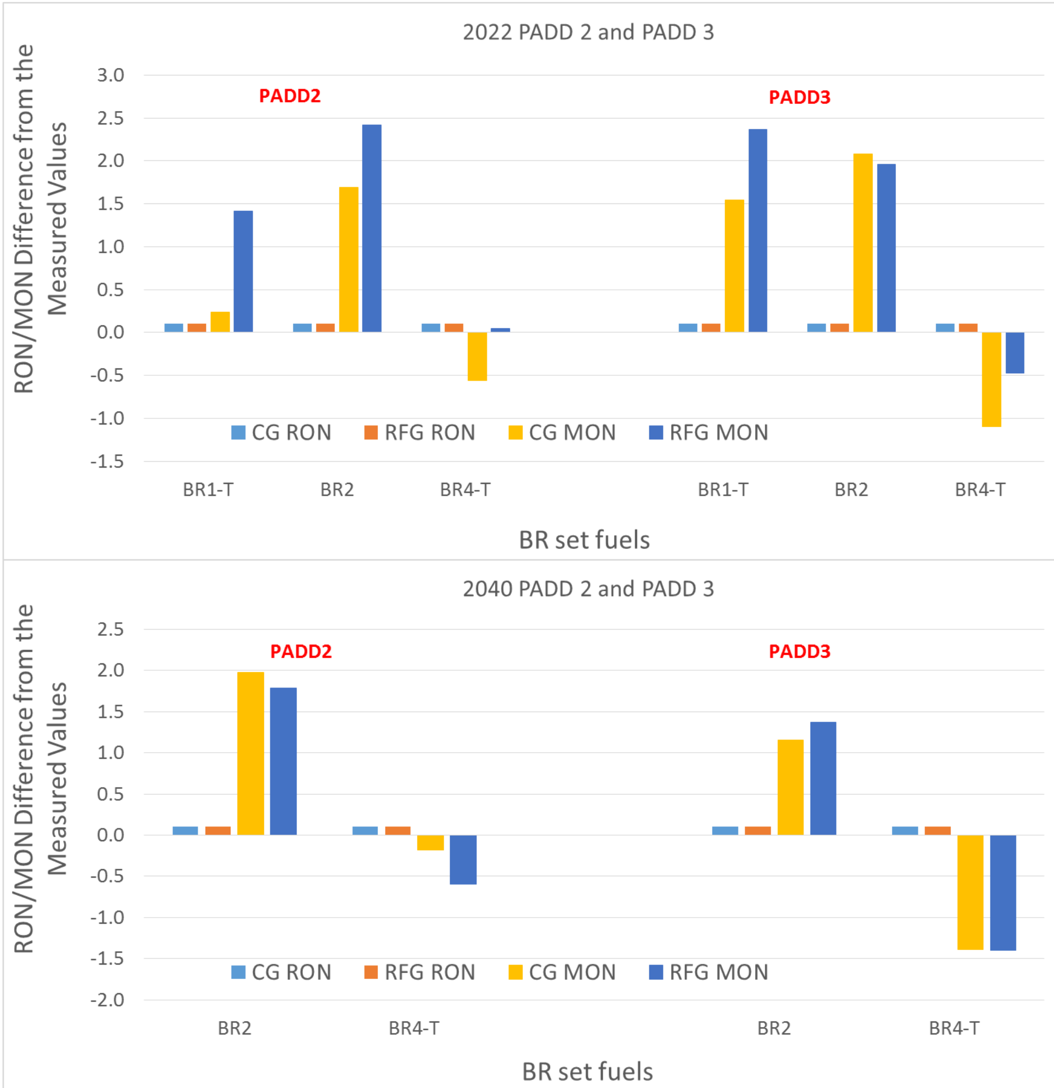


Figure 5-30. The Comparison of BR HOF Gasoline RONs and MONs from LP Modeling with the Lab–measured Values in Year 2022 and 2040

5.2.1.1 Exported Gasoline of the Aggregate Refinery with BR Fuel Production

The product slates of aggregate refineries with BR fuels production in 2022 and 2040 are displayed in Appendix 1 in Tables A1-15 and A1-16. Some key elements are discussed below.

The gasoline export of each refinery with BR/BR-T fuel production varies with PADD, fuel and year. The results are shown in Table 5-15.

Table 5-15. Ratio of Gasoline Export/Total Gasoline for BR Set Fuels Produced in Aggregate Refineries

		PADD 2			PADD 3		
2022	Base Case	0.05%			10.3%		
	BR/BR-T	BR1-T	BR2	BR4-T	BR1	BR2	BR4-T
	Gasoline export/total	0.05%	0.24%	2.2%	9.0%	17.6%	17.8%
	Base Case	0.1%			23.9%		
2040	BR/BR-T		BR2	BR4-T		BR2	BR4-T
	Gasoline export/total	--	9%	15%	--	45%	45%

In 2022, the ratio of export to domestic gasoline is 0–2% in PADD 2, comparable to the export amount in the base case. In contrast, the export gasoline share in PADD 3 is in the range of 9-18%, much higher than the base case export share, except for BR1 fuel.

From 2022 to 2040, the export gasoline share of the total gasoline production increases in both PADDs, much more than in the base case. This is driven by two factors: the increase of HOF share from 50% to 100% with high bio-blend (27% for BR2 and BR4-T) that reduces the demand for gasoline BOB, and the lower G/D ratio based on the EIA projection.

5.2.1.2 The Components of Regular and HOF Gasoline Pools of the BR Fuels in Aggregate Refineries

In 2022, the LP modeling shows that BR1-T, BR-2 and BR4-T set fuels can be produced in PADD 2, coupled with minimal or no gasoline export. Therefore, only the components of the BAU and HOF gasolines of the BR set fuels in PADD 2 are shown in the Figure 5-31 below.

BR2 fuel can be produced in the PADD 2 Aggregate refinery, owing to its high RON BR blending (27 vol%) and mid RON demand of 97. In contrast, the low BR blending (9 vol%) for BR1 and the high octane demand (101 RON) for BR 4 prohibits the production of those two fuels in the PADD 2 Aggregate refinery, yielding no feasible solutions in LP modeling. However, using toluene as a surrogate to produce fuels BR2-T and BR4-T (with the same bio-content blending and octane demand), the LP modeling of two cases resulted in feasible solutions for the purpose of this study.

The gasoline components of BR2 are different from those of BR1-T and BR4-T. The BAU gasoline of BR2 is dominated by reformate, while BR1-T and BR4-T gasolines have much less reformate and are balanced among FCC, alkylate, isomerate and naphtha. For HOF gasoline, BR2 is dominated by FCC stream and alkylate, with a small volume share of reformate. BR1-T and BR4-T HOF gasolines are dominated by FCC as well, but with a much smaller share of alkylate, owing to the fact that the toluene blend (high octane, moderate boiling point) decreases the demand for the “ideal” alkylate stream (high octane, moderate boiling point and not limited by aromatics cap).

In PADD 3, the production of the BR set fuels is coupled with some exports (9–18 vol% of total gasoline production). Thus, the components of all these gasoline pools, BAU, HOF and export gasolines, are displayed for comparison in Figure 5-32.

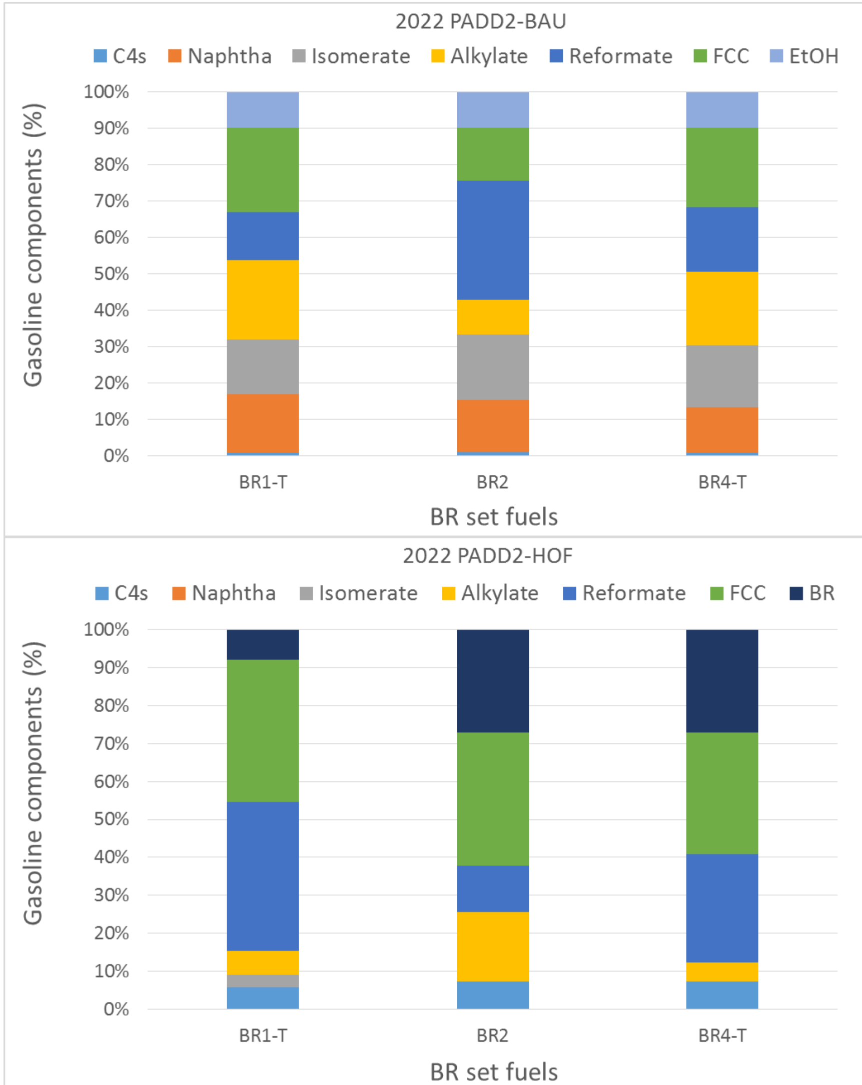


Figure 5-31. BAU and HOF Gasoline Components of BR/BR-T Fuels Produced in PADD 2 Refinery in 2022

In PADD 3, one more BR fuel modeling case (BR1) yielded feasible solutions, suggesting that the PADD 3 refinery is more flexible than the PADD 2 refinery and so better able to meet challenging demands. The BAU gasoline and HOF gasoline of BR1 have similar component shares, mainly consisting of reformate, FCC, and alkylates. However, the former has a sizable share of naphtha, while HOF gasoline has sizeable share of isomerate. The inexpensive, low-octane naphtha blending in the BAU pool can prevent octane giveaway and benefit refinery economics, while the light, volatile but high-octane isomerate blending in HOF gasoline can offset the heavy BR stream without losing octane benefit. The export gasoline of the BR1 set is mainly reformate and alkylate.

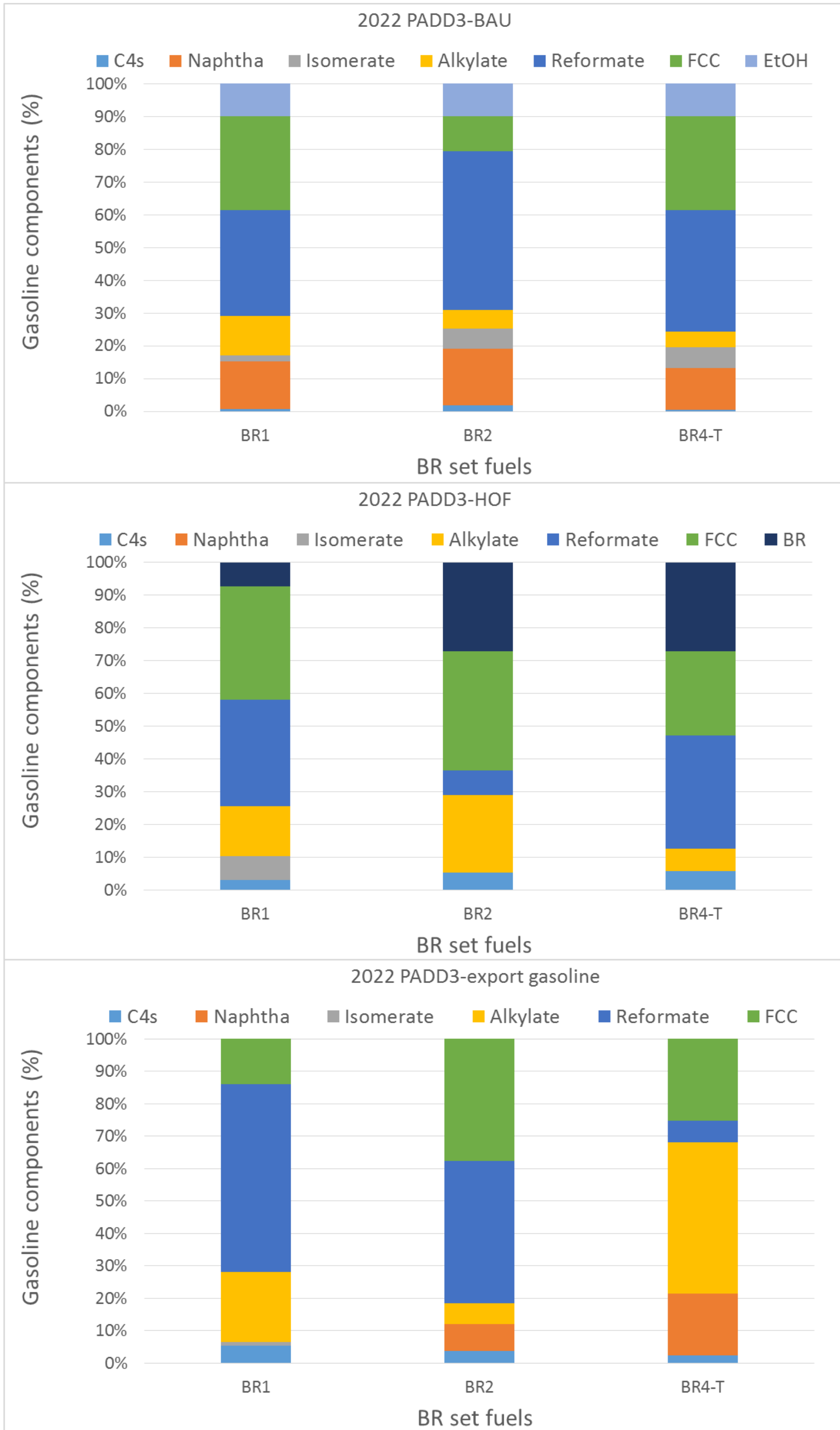


Figure 5-32. Components of BAU, HOF and Exported Gasoline of BR/BR-T Fuels Produced in PADD 3 Refinery in 2022

For BR2 fuel, the high volume of BR blending (27 vol%) and mid-level octane demand results in a low demand for reformate stream blending as an octane booster in the HOF gasoline pool. The BAU gasoline has a high-volume blending of reformate balanced by lighter isomerate and naphtha to meet distillation specifications. The export gasoline has small share of alkylate and is dominated by reformate and FCC stream, balanced with lighter streams of naphtha and C4s.

The production of BR 4 fuels in PADD 3 is rather challenging, and the LP modeling can only yield feasible solutions by using toluene as a surrogate, as was the case in PADD 2. It is interesting to observe that although the BR4-T HOF gasoline's component shares are similar in PADD 2 and in PADD 3, BAU gasoline component distributions are different. Compared with the BAU gasoline produced in PADD 2, the BAU in PADD 3 has less isomerate and more reformate, probably because PADD 3 refineries produce a higher share of RFG, which has a lower RVP than CG, limiting the blending of isomerate. The export gasoline with BR4-T production is very different from that of BR1 and BR2, being dominated by a high share of alkylate. This might suggest that toluene serves as an octane booster with good distillation properties, thus somewhat easing the alkylate blend demand in the BAU and HOF pool.

In 2040, in both PADD 2 and PADD 3, the export gasoline coupled with BR set fuels production increases greatly, reaching 18%–36 vol%. Thus, it is important to compare the components of both domestic (all HOF gasoline) and export gasolines of BR/BR-T set fuels, shown in Figure 5-33.

In 2040, only the modeling of BR2 gasoline yielded feasible solutions in both PADD 2 and PADD 3. With the toluene surrogate, the modeling of BR4-T production was able to reach feasible solutions.

For BR2, the domestic gasoline produced in PADD 2 has much high isomerate/naphtha blending, owing to its less stringent RVP specification. In contrast, the BR2 produced in PADD 3 has more FCC and alkylate. Similarly, the BR4-T produced in PADD 2 has more isomerate than that of PADD 3. With the demanding octane and RVP specification, the BR4-T produced in PADD 3 consists almost entirely of high octane components: reformate, BR-T (toluene), C4s and FCC. In contrast, the export gasoline is dominated by alkylate, with increased shares of naphtha and isomerate (relative to the HOF gasolines).

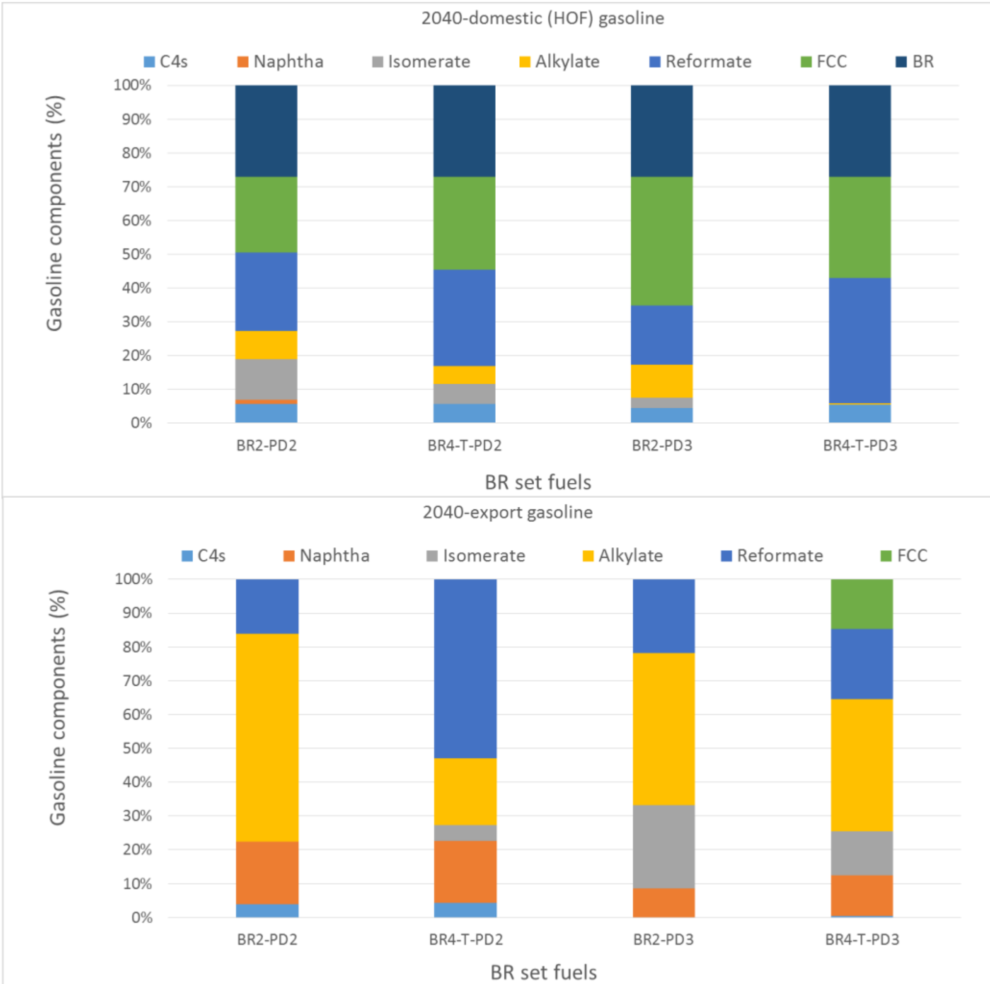


Figure 5-33. Components of BR/BR-T Gasolines (all HOF gasoline) Produced in PADD 2 (PD2) and PADD 3 (PD3) in 2040

5.2.1.3 Reformer Severity and Product Volume of BR Fuels Produced in Aggregate Refineries

The reformer severity and product volume of aggregate refineries with BR fuels production in 2022 is shown in Table 5-16. For each case, the reformer runs with high severity. BR 2 has relatively lower severity and contribution (Sev × BPD) than the other BR or BR-T fuels, suggesting the relative ease of producing it (mid RON target).

In 2040, the results show that in order to produce the BR (or BR-T) fuels, the PADD 2 and PADD 3 refinery increased their reformer severity significantly, relative to the PADD base cases, suggesting the challenges to produce such fuels. See Table 5-17.

Table 5-16. Reformer Severity and Product Volume of Aggregate Refineries with BR Fuels Production in 2022

Region/year	PADD 2 2022			PADD 3 2022		
Fuel	BR1-T	BR2	BR4-T	BR1	BR2	BR4-T
Total Reforming Capacity (BPD)	656,009	567,276	586,482	1,826,744	1,738,144	1,739,864
Avg Reforming Severity	99.2	95.2	97.4	96.7	93.9	95.5
Sev×BPD (in 1000)	65,070	54,016	57,101	176,673	163,234	166,209

Table 5-17. Reformer Severity and Product Volume of Aggregate Refineries with BR Fuels Production in 2040

Year-Region	2040 PD2	2040 PD3	2040 PD2	2040 PD3
Fuel	BR2	BR2	BR4-T	BR4-T
Total Reforming Capacity (BPD)	529,828	1,778,965	710,993	1,843,911
Avg Reforming Severity	98.6	97.3	100.8	98.5
Sev × BPD (in 1000)	52,256	173,136	71,653	181,646

5.2.1.4 The Hydrogen Supply of Aggregate Refineries with BR/BR-T Fuels Production

The hydrogen supply for PADD 2 and PADD 3 refineries producing BR or BR-T fuels in 2022 and 2040 is shown and compared in Figures 5-34 and 5-35.

The figures show that in both 2022 and 2040, the PADD 3 refinery supplied (based on demand) more hydrogen than their PADD 2 counterparts. The refineries with various BR or BR-T fuels production demanded (or were supplied) similar amount of hydrogen, in line with the hydrogen use of PADD 3 refinery with E set fuels production. From 2022 to 2040, the hydrogen supply increases slightly.

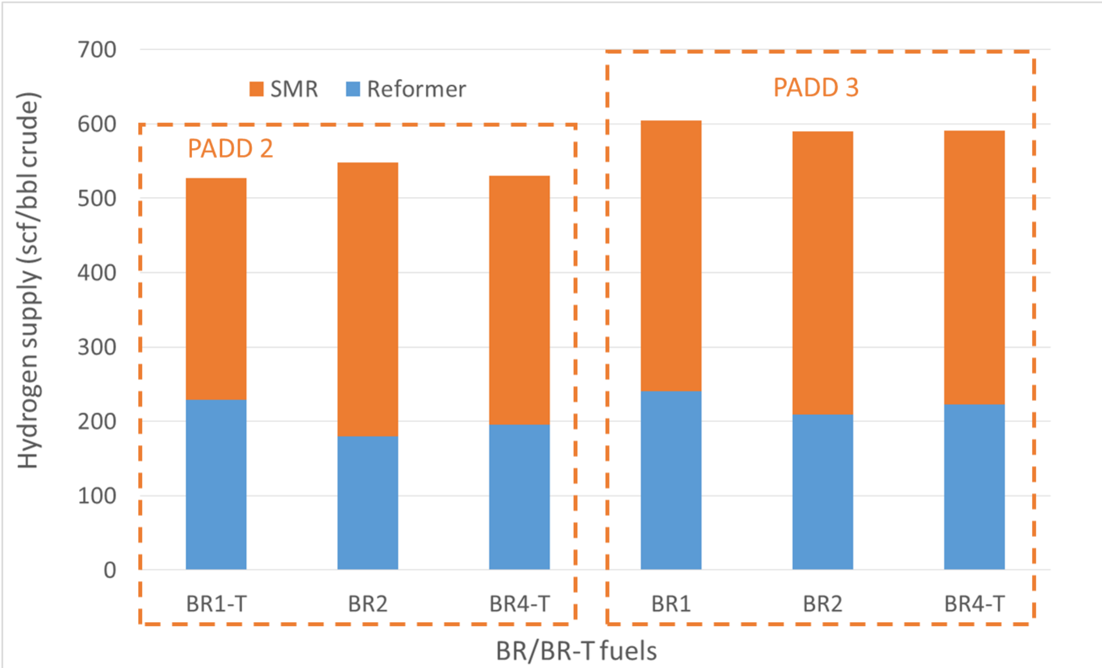


Figure 5-34. Hydrogen Supply for Aggregate Refineries with BR Fuel Production in 2022

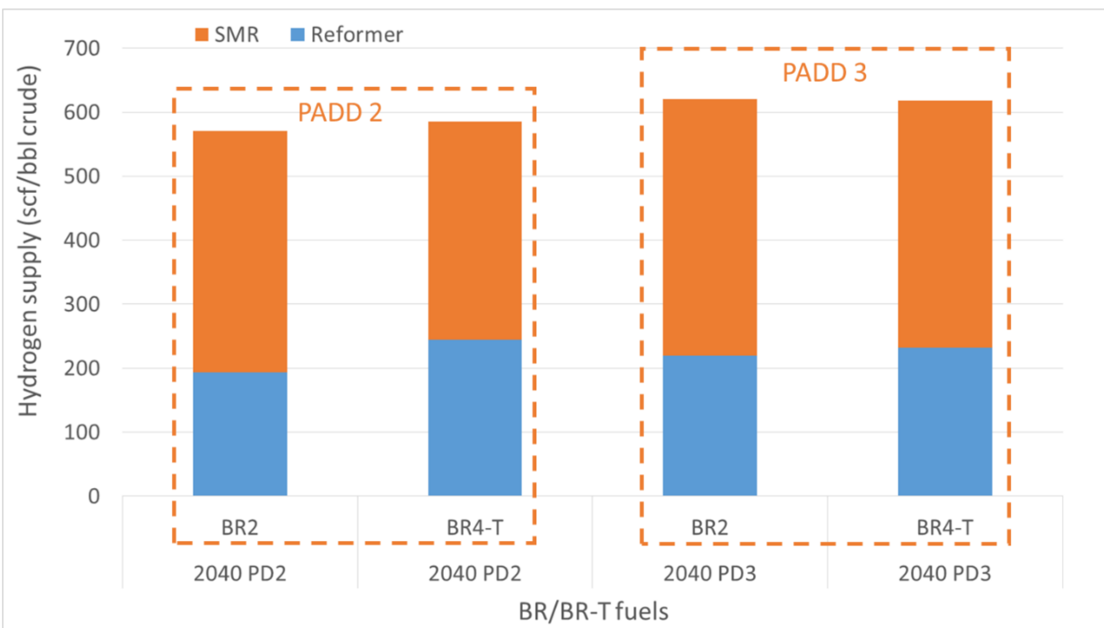


Figure 5-35. Hydrogen Supply for Aggregate Refineries with BR Fuel Production in 2040

<u>5.2.2 LP Modeling Results of Configuration Refineries with BR Fuel Production</u>

The LP modeling feasibility of the configuration refineries with BR fuels production is summarized in Table 5-18.

Table 5-18. Summary of LP Modeling Feasible Solutions of Configuration Refineries with BR/BR-T Fuel Production

	Configuration 2022				Configuration 2040			
Fuel	CRK	LtCOK	HvyCOK	COKHCK	CRK	LtCOK	HvyCOK	COKHCK
Fuel BR1	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
Fuel BR2	Feasible	Feasible	Feasible	Infeasible	Feasible w/TOL	Feasible w/TOL	Feasible w/TOL	Infeasible
Fuel BR3	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible	Infeasible
Fuel BR4	Feasible w/TOL	Feasible w/TOL	Feasible w/TOL	Infeasible	Feasible w/TOL	Feasible w/TOL	Feasible w/TOL	Infeasible

TOL: toluene

Consistent with the results of PADD refineries with BR fuels production, most BR cases cannot yield feasible solutions in LP modeling (because of the high boiling point of bioreformate leading to high T90 of the blended gasoline), except for a few cases of BR2. By using the toluene surrogate, several more LP modeling cases were solved for BR2-T and BR4-T.

The BR/BR-T HOF gasoline RONs and MONs resultant from LP modeling are compared with the lab-measured values of the fuels that are used for engine tests, the lab-measured values are shown in the Table 5-19 below and comparisons are shown in Figure 5-36 .

Table 5-19. The Lab–Measured RON and MON of BR HOF Gasolines

	BR2/BR2-T	BR4/BR4-T
LAB HOF RON	97.3	101.0
LAB HOF MON	87.0	90.3

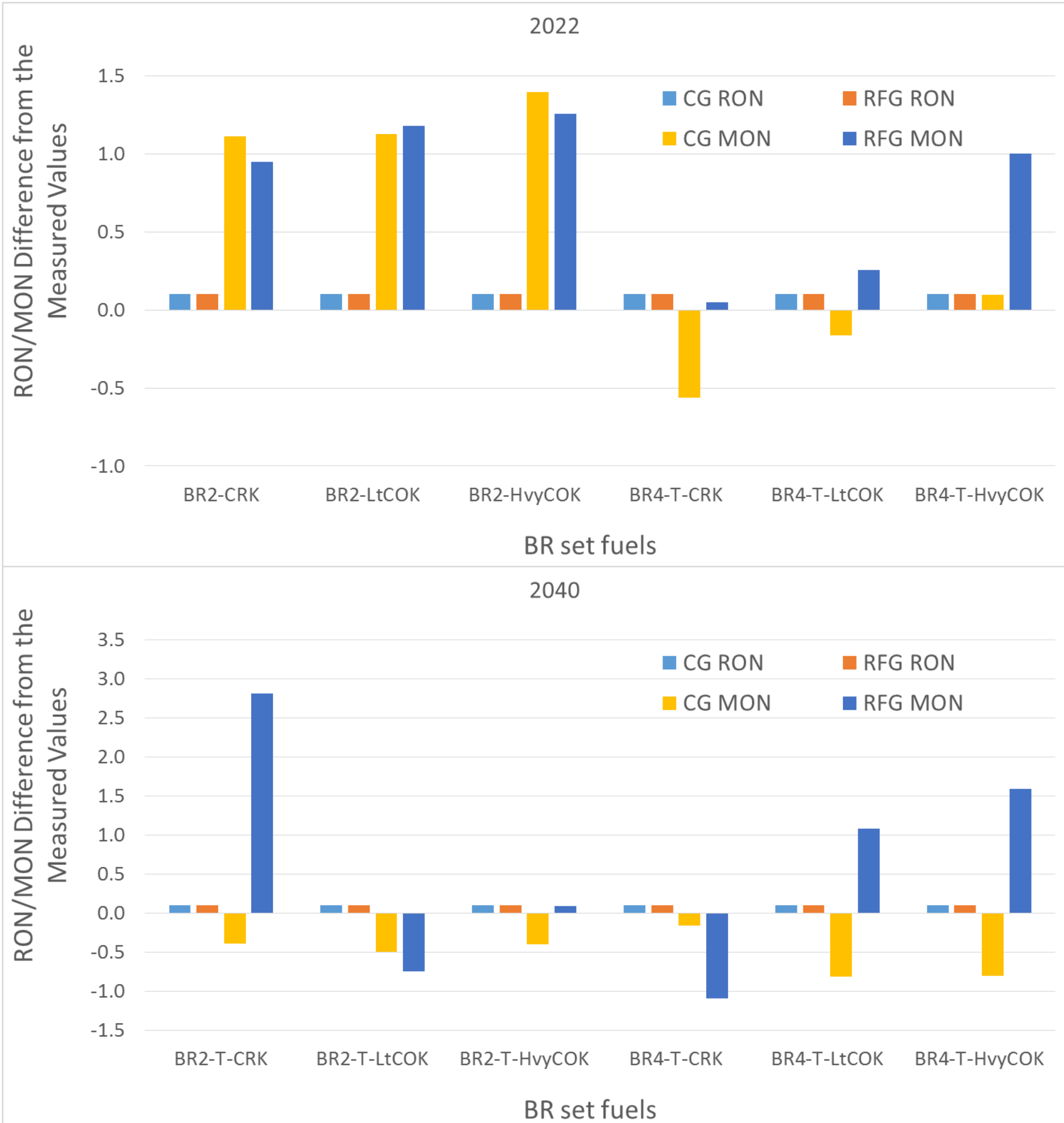


Figure 5-36. The Comparison of BR Set HOF Gasoline RONs and MONs from LP Modeling with the Lab–Measured Values

For all the cases, the LP modeling resultant RONs match the lab–measured values. The comparison of LP modeling resultant MONs with lab–measured MONs shows different patterns for different gasoline, refinery configuration, and year, with the difference in the range of -0.5 to +2.7. Again, the different divergence of LP modeling MONs from the lab–measured data indicates the divergence of fuel OS that is expected to have secondary impact on engine performance. The different MONs of each gasoline pool is fundamentally determined by the gasoline components, which are in turn governed by LP modeling.

5.2.2.1 Exported Gasoline in Configuration Refineries with BR Set Fuel Production

The LP modeling results for 2022 and 2040 are summarized in tables in Appendix 1 in Tables A1-17 and A1-18, respectively. Some key results are discussed here.

Gasoline export shares relative to the total gasoline BOB produced in each configuration refinery are listed in Table 5-20.

Table 5-20. Exported Gasoline Share in Configuration Refinery with BR/BR-T Fuel Production in 2022 and 2040

	BR2			BR4-T		
2022	CRK	LtCOK	HvyCOK	CRK	LtCOK	HvyCOK
	0%	1%	0%	0%	0%	0%
	BR2-T			BR4-T		
2040	CRK	LtCOK	HvyCOK	CRK	LtCOK	HvyCOK
	0%	15%	11%	12%	17%	15%

For all the configuration refinery base cases, there is only 10 bbl/day of gasoline export, or 0.01% export of all the gasoline BOB. Like the base cases, the configuration refineries with BR2/BR4-T production in 2022 have minimal or no gasoline export. In contrast, the configuration refineries in 2040 have 11%–17% gasoline export as a result of higher BR blending, 100% HOF share, and lower G/D ratio.

5.2.2.2 Components of BAU, HOF and Exported Gasoline Pools

As noted, in 2022, the configuration refineries with BR/BR-T set fuels have minimal or no exports, thus only the components of BAU and HOF gasolines are displayed in Figure 5-37.

BR2 BAU gasoline produced in CRK, LtCOK, and HvyCOK refineries consists mainly of reformate and naphtha, while the HOF gasolines consist mainly of FCC, alkylate, and reformate with 27 vol% BR bioreformate. Each HOF fuel also includes about 5 vol% C4s, which not only have high octane numbers but, with a low boiling point, can balance the high-boiling BR stream to meet distillation specifications. BR4-T BAU gasoline is dominated by reformate, FCC, naphtha, and isomerate, while the HOF fuels are dominated by reformate, FCC, and alkylate. The C4s share in BR4-T increases to 6% from 5% in BR2, which helps balance the increased amount of heavy reformate.

In 2040, about 20 vol% of total gasoline is exported. The components of both domestic and export gasoline produced in the configuration refineries with BR/BR-T fuels production are shown in Figure 5-38.

In 2040, the domestic gasoline and export gasoline component shares are very different. The former consists mainly of reformate and FCC, in addition to a large share of bioreformate. The latter is dominated by alkylate, isomerate, and naphtha for BT2-T and reformate, alkylate and isomerate for BT4-T.

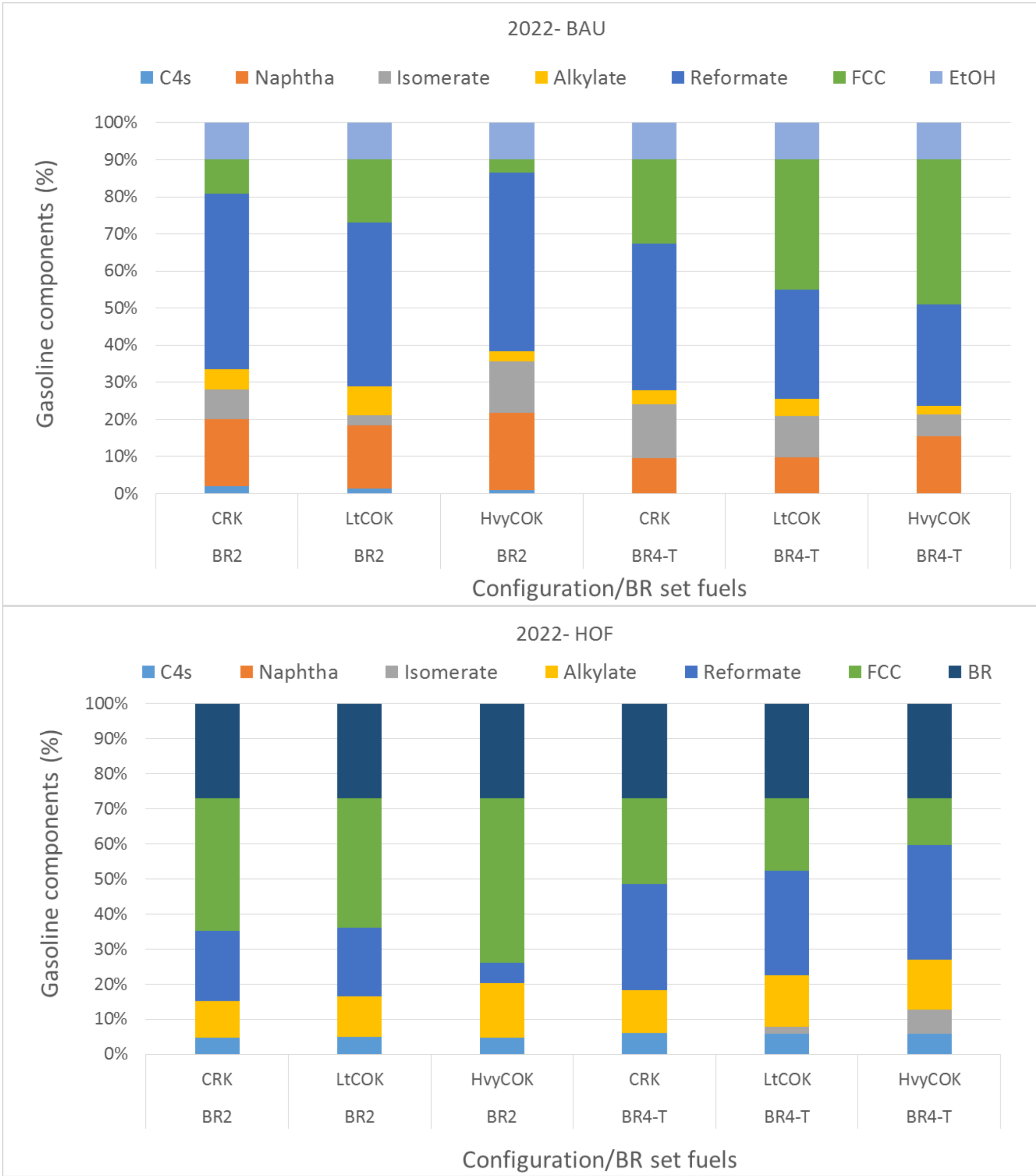


Figure 5-37. Gasoline Components of Configuration Refineries with BR/BR-T Fuel Production in 2022

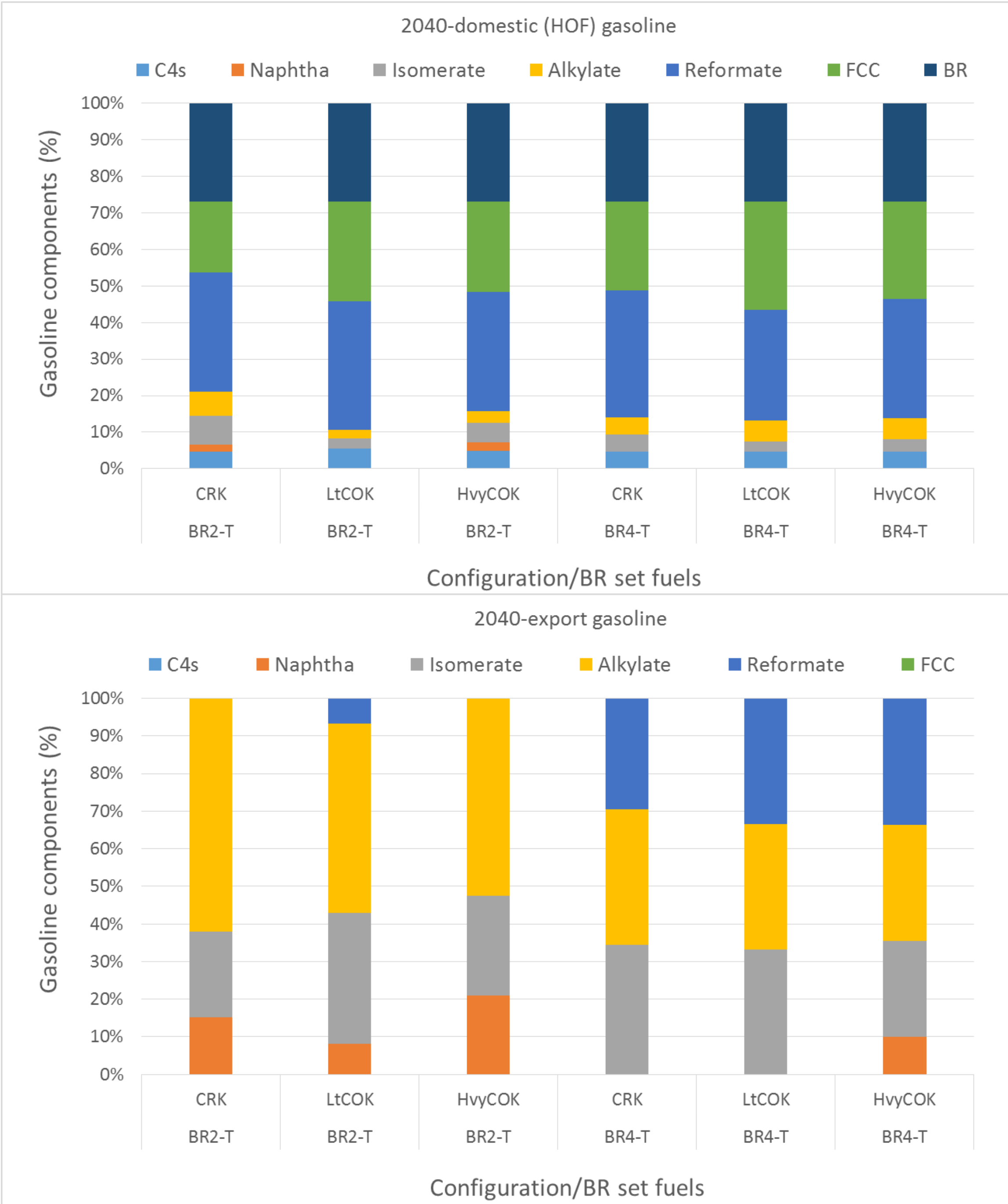


Figure 5-38. Gasoline Components of Configuration Refineries with BR/BR-T Fuel Production in Year 2040

5.2.2.3 Refinery Reformer Severity and Product Volume

The configuration refineries producing BR/BR-T fuels ran their reformers with various severity and volume levels, as shown in Table 5-21.

Table 5-21. Configuration Refinery Reformer Severity and Product Volume with BR Set Gasoline Production in 2022 and 2040

Year	Configuration	CRK	LtCOK	HvyCOK	CRK	LtCOK	HvyCOK
2022	Fuel	BR2	BR2	BR2	BR4-T	BR4-T	BR4-T
	Total Reforming Capacity (BPD)	34,064	33,393	27,625	36,472	32,249	33,192
	Avg Reforming Severity	99.0	100.0	99.2	97.9	99.0	97.0
	Sev*BPD (in 1000)	3,372	3,339	2,741	3,571	3,193	3,220
2040	Fuel	BR2-T	BR2-T	BR2-T	BR4-T	BR4-T	BR4-T
	Total Reforming Capacity (BPD)	29,906	33,240	28,702	35,879	33,875	33,397
	Avg Reforming Severity	93.2	92.0	93.5	101.0	101.0	101.0
	Sev*BPD (in 1000)	2,787	3,057	2,684	3,624	3,421	3,373

In 2022, for both BR2 and BR4-T, configuration refineries would have to run reformers with very high severity, about 97-100, much higher than that of the base cases (90–91), reflecting the challenges of meeting high octane demand (97 for BR2 and 101 for BR4). In 2040, the BR 2 case reformer severity of 92–93.5 was much lower than reformer severity of the BR4-T cases of 101, suggesting that BR2 is easier to produce than BR4-T.

5.2.2.4 Hydrogen Supply for Producing BR Fuels in Configuration Refineries

The hydrogen supply for the configuration refineries producing BR/BR-T fuels is shown in Figures 5-39 and 5-40 for 2022 and 2040, respectively.

For all cases in 2022 and 2040, the hydrogen supply/demand in each configuration refinery is in line with that of the configuration base cases. As with the configuration refineries with E set fuels production, the hydrogen supply/demand of the refineries with BR/BR-T fuels production increased with increasing configuration complexity.

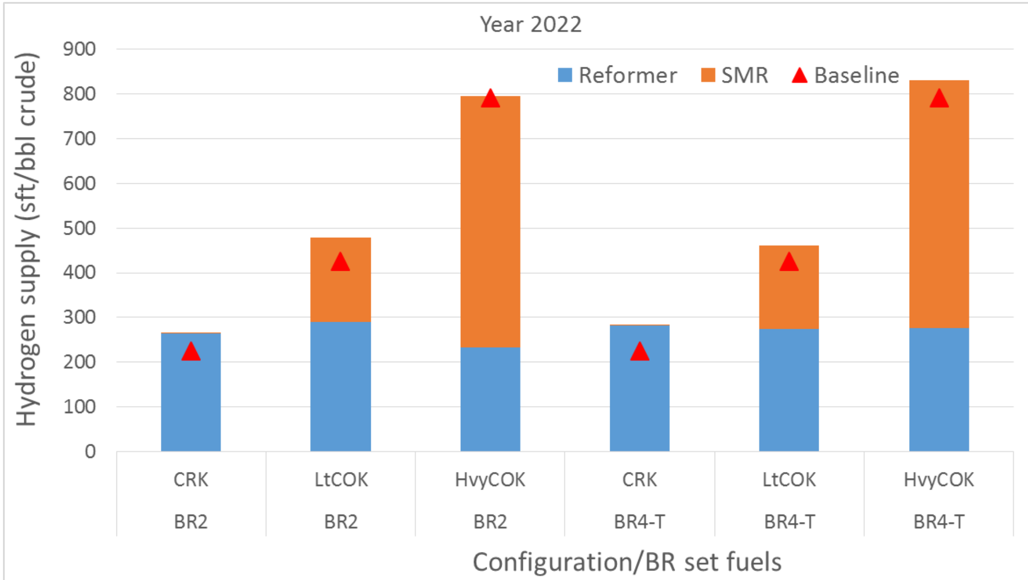


Figure 5-39. Hydrogen Supply for Configuration Refineries with BR/BR-T Fuel Production in 2022

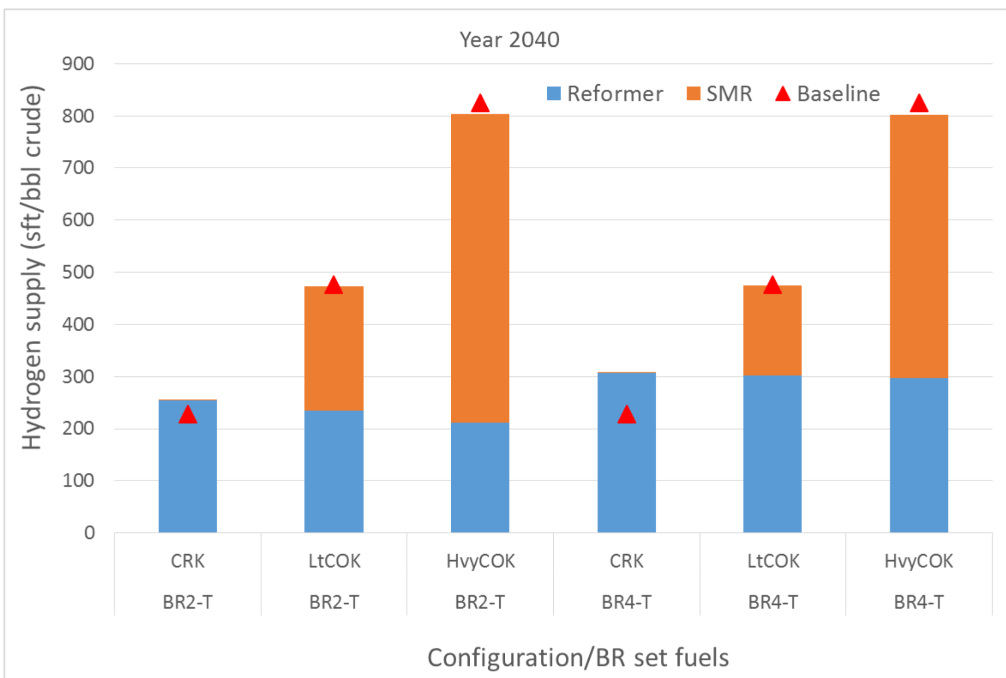


Figure 5-40. Hydrogen Supply for Configuration Refineries with BR/BR-T Fuel Production in 2040

6. Energy Intensities and Efficiencies for Overall Refinery Products and for Gasoline Production

The LP modeling results were processed to obtain the overall refinery energy efficiencies, the energy efficiencies of individual refinery products, and the material/energy input for individual refinery products. This information was imported into the GREET 2016 model to calculate the GHG emissions during the fuel production (refinery operation) stage.

6.1 Definition of Energy Intensity and Efficiency

6.1.1 Overall Refinery Energy Intensity and Efficiency

The refinery energy intensity and efficiency evaluation metric was developed in the previous research of Elgowainy [29] and Han et al. [5].

Overall refinery intensity is defined as total energy inputs (e.g., crude oil, butane, natural gas, hydrogen, electricity, other feedstock, etc.) divided by total energy outputs in refining products (e.g., gasoline, jet fuel, diesel, LPG, residual fuel oil [RFO], pet coke, etc.):

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

Where:

C_m is the amount of crude input m in barrels.

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

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

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

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

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

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

Energy intensity reflects the amount of resources needed to produce one unit of refinery energy product. Taking the reciprocal of energy intensity gives another important parameter: energy efficiency.

Overall refinery energy efficiency is defined as total energy output in refining products (e.g., gasoline, jet fuel, diesel, LPG, residual fuel oil [RFO], pet coke, etc.) divided by total energy inputs (e.g., crude oil, butane, natural gas, hydrogen, electricity, other feedstock, etc.), as shown in Equation 2. It should be noted that the refinery efficiency applies to refinery operation to produce gasoline BOB and other refinery products, thus the ethanol volumes or bioreformate volumes for blending into gasoline BOB are not counted in the refinery energy inputs or outputs.

$$\eta_{LHV} = \frac{\sum_n (P_n \times LHV_n)}{\sum_m (C_m \times LHV_m) + \sum_0 (OI_o \times LHV_o) + NG_{purchased,LHV} + H_{2,purchased,LHV} + Electricity_{purchased}} \quad (2)$$

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

Energy balance results are needed for the energy efficiency calculation. These can be calculated from the volumetric and mass input and output results from the LP model, using the lower heating values (LHVs) of products. For solid products (e.g., delayed coke), GREET's default LHVs are used. The LHVs of gaseous products (H_2, CH_4, butane, etc.) are obtained from Green and Perry [52]. The LHVs of liquid products are estimated from the higher heating values (HHVs) that are calculated by using the following regression formula from the publication *API Basic Petro Data* [53]:

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

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

6.1.2 Energy Intensity and Efficiency for Gasoline BOB Production

The overall refining efficiency calculation considers an entire refinery as a single system, taking into account the refinery inputs and outputs. Although the overall refining efficiency is critical for estimating the total processing energy use per unit of energy in all refinery products, the total processing energy use does not consider the differences in the energy intensities of the various refining units that produce the streams that make up the different product pools. Thus, for each individual refinery product, the energy product (e.g., gasoline) energy efficiency must be further derived. This is implemented by energy analysis at the process unit level, using the energy intensity of the process units to obtain an energy consumption ratio for each product and account for its contribution to the various product pools. The process-level efficiency metric and its calculation were developed and documented by Han et al. [5].

Figure 6-1 shows a schematic of a generic refinery process unit with various feeds or energy inputs (F_1 through F_k) and various yield streams or energy outputs (Y_1 through Y_J). Refinery energy inputs (e.g., crude, NG, hydrogen, electricity, and other hydrocarbons) are denoted by $Input_i$. Refinery energy inputs and their derivatives propagate through successive process units to produce intermediate products and, eventually, final products. Thus, each stream's energy (feed F_k or yield Y_j) through a process unit carries certain energy burdens associated with the refinery inputs ($Input_1$ through $Input_I$). For example, $EI_{i,j}$ in Figure 6-1 denotes the energy burden of a specific refinery input i that contributes to the production of the unit energy of yield stream j.

The sum of all energy burdens for a particular yield stream *j* is defined as the total energy intensity of that stream: $\Sigma EI_{i,j}$ (i.e., the share of the total amount of refinery input energies required to produce the unit energy of that stream). Note that the inverse of energy intensity represents the energy efficiency. By estimating the production energy intensity of all streams, and aggBAUating them for the products that make various final product pools (e.g., gasoline pool, distillate pool), we can obtain final product-specific efficiencies.

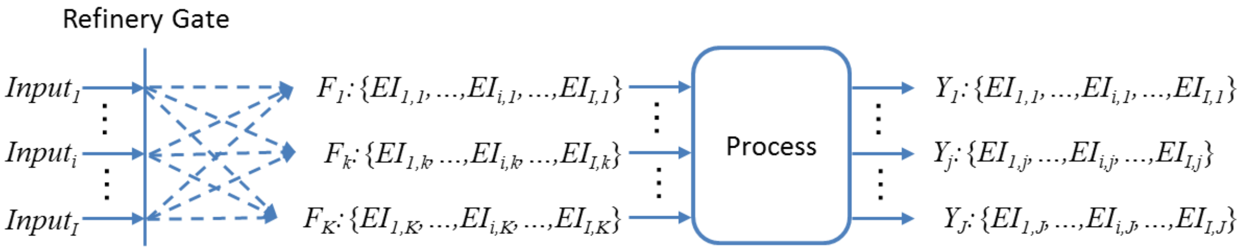


Figure 6-1. Schematic Flow of a Generic Refinery Process Unit

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

$$EI_{i,j} = (\sum_k (F_k \times EI_{i,k})) \times S_j \div Y_j \qquad (4)$$

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

In an energy-based allocation, the energy content of each stream is used to calculate its share (S_j^E). This is the most commonly used allocation metric in the lifecycle of energy products, because the significance of energy products is in their energy value. The energy-based shares of a yield stream *j* (S_j^E) can be expressed by the following equation:

$$S_j^E = Y_j \div \sum_j Y_j \qquad (5)$$

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

$$EI_{i,j} = \left(\sum_k (F_k \times EI_{i,k})\right) \times \left(\mathrm{Y_j} \div \sum_{\mathrm{j}} \mathrm{Y_j}\right) \div Y_j = \left(\sum_k F_k \times EI_{i,k}\right) \div \sum_{\mathrm{j}} \mathrm{Y_j} \qquad (6)$$

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

By using the process unit level allocation approach, energy intensity and efficiency can be calculated for gasoline production. By tracking and grouping different gasoline component streams dictated by LP modeling, energy intensity and efficiency can be calculated for the BAU gasoline pool, HOF gasoline pool and export gasoline pool.

6.2 E Set Gasolines—Energy Intensity and Efficiency for Refinery and for Gasoline BOB

The energy intensity and efficiency for overall refinery operation and for gasoline BOB production are calculated with methodology described above and discussed below. It is worth noting that the energy intensity/efficiency and corresponding GHG emissions (derived from the energy uses) are resultant from refinery operation to produce refinery products. The refinery operation is governed by LP modeling, which optimizes refinery operations for profit maximization, not for efficiency maximization.

6.2.1 Aggregate Refinery Base Case Intensity and Efficiency Overview

The refinery LP model generates the volume flow and mass flow rates for all refinery inputs, outputs and intermediate streams as well as utility consumption rates (e.g., electricity, steam, process fuels, water and catalysts). In order to calculate GHG emissions of transportation fuels, these refinery LP model results were converted to energy flow rates and balances. Upon completion of the conversion, the energy intensity—the energy input for producing one MJ of refinery energy product—was calculated. Using the established process-level allocation method described above, the energy intensity for individual refinery products (gasoline BOB, diesel, LPG, etc.) was also determined. The present study focuses on the energy intensity and efficiency for overall refinery operation and that for gasoline BOB production.

6.2.1.1 Aggregate Refinery Base Case Energy Intensity and Efficiency

For the PADD base cases, the breakdown of overall refinery energy inputs per MJ of refinery energy products (including BAU gasoline BOB and other refinery products) is shown in Figure 6-2.

In each of the three years shown, CA refineries use more natural gas than PADD 2 and PADD 3 refineries do, and the difference is much more pronounced in 2022 and 2040. From 2015 to 2022 and 2022 to 2040, there is a significant increase of "heavy[9]" feedstock input to PADD 3 refineries, coupled with a decrease in crude input.

From 2015 to 2022 and to 2040, there is noticeable increase of heavy oil used in PADD refineries. These results are a combination of economic optimization and forecast estimates. For year 2015, the PADD 3 refinery model optimized to a lower volume of purchased heavy feed than that reported by EIA. In 2022 and 2040, these volumes are not explicitly forecasted, however we put tighter bounds on this constraint reflective of historical purchases.

[9] "Heavy" feedstock is unfinished heavy oil purchased from other refineries (e.g., vacuum gas oil, slurry oil, atmospheric residual, etc.).

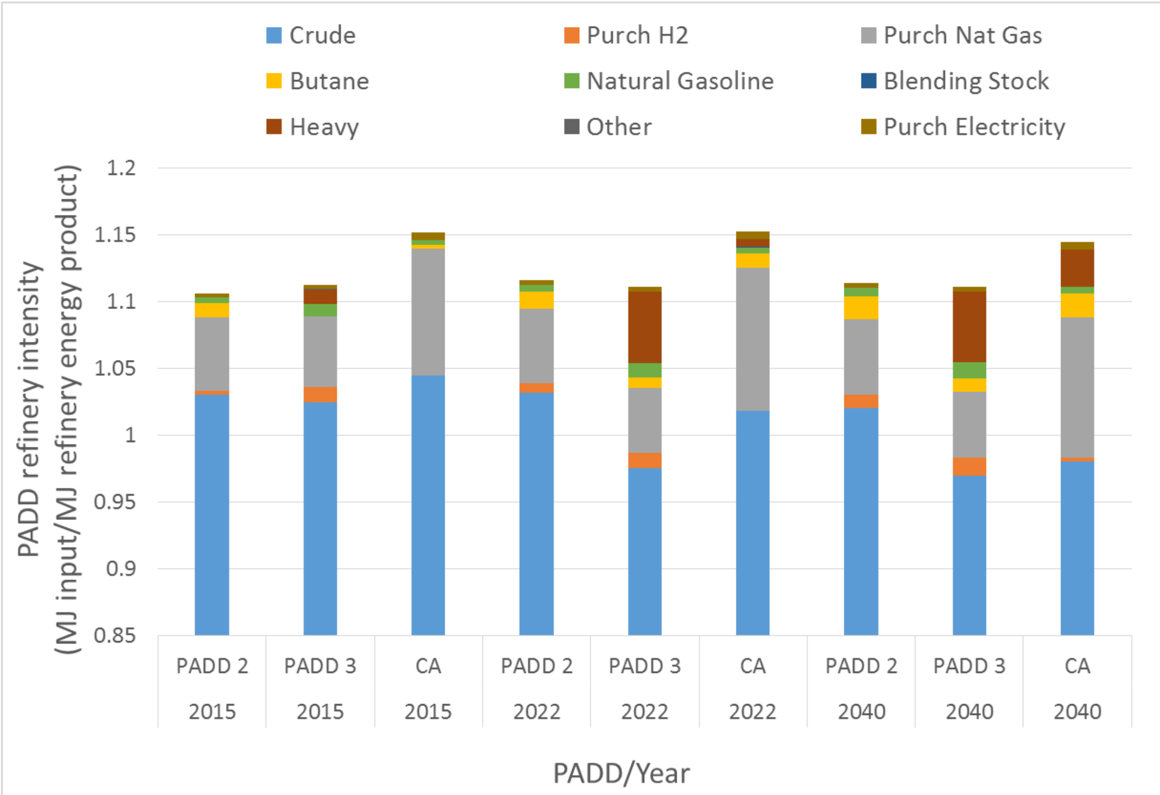


Figure 6-2. The Breakdown of Refinery Energy Inputs for Aggregate Refinery Base Cases in Three Regions and Three Years

6.2.1.2 Aggregate Refinery Base Cases Gasoline BOB Production Intensity and Efficiency

Gasoline production intensity was also calculated and is shown in Figure 6-3. For the base cases, all domestic gasoline is BAU gasoline.

For each modeled case, the gasoline BOB production energy intensity has more input from crude and less input from natural gas compared with its overall refinery energy intensity. The allocation of energy inputs (e.g., crude and natural gas) to refinery products (e.g., gasoline) depends on the energy uses of units from which the refinery product streams are produced (e.g., alkylate, FCC) and from which refinery products receive energy/burdens (e.g., hydrogen). It is worth mentioning that export gasoline only contains BOB and has no ethanol content.

The overall refinery efficiency and gasoline production efficiency of the PADD base cases are shown in Figure 6-4. As described above, refinery efficiency is defined as the energy content of all refinery energy products divided by energy content of all refinery energy inputs, and it is the reciprocal of refinery energy intensity. Similarly, gasoline production efficiency is the reciprocal of gasoline energy intensity.

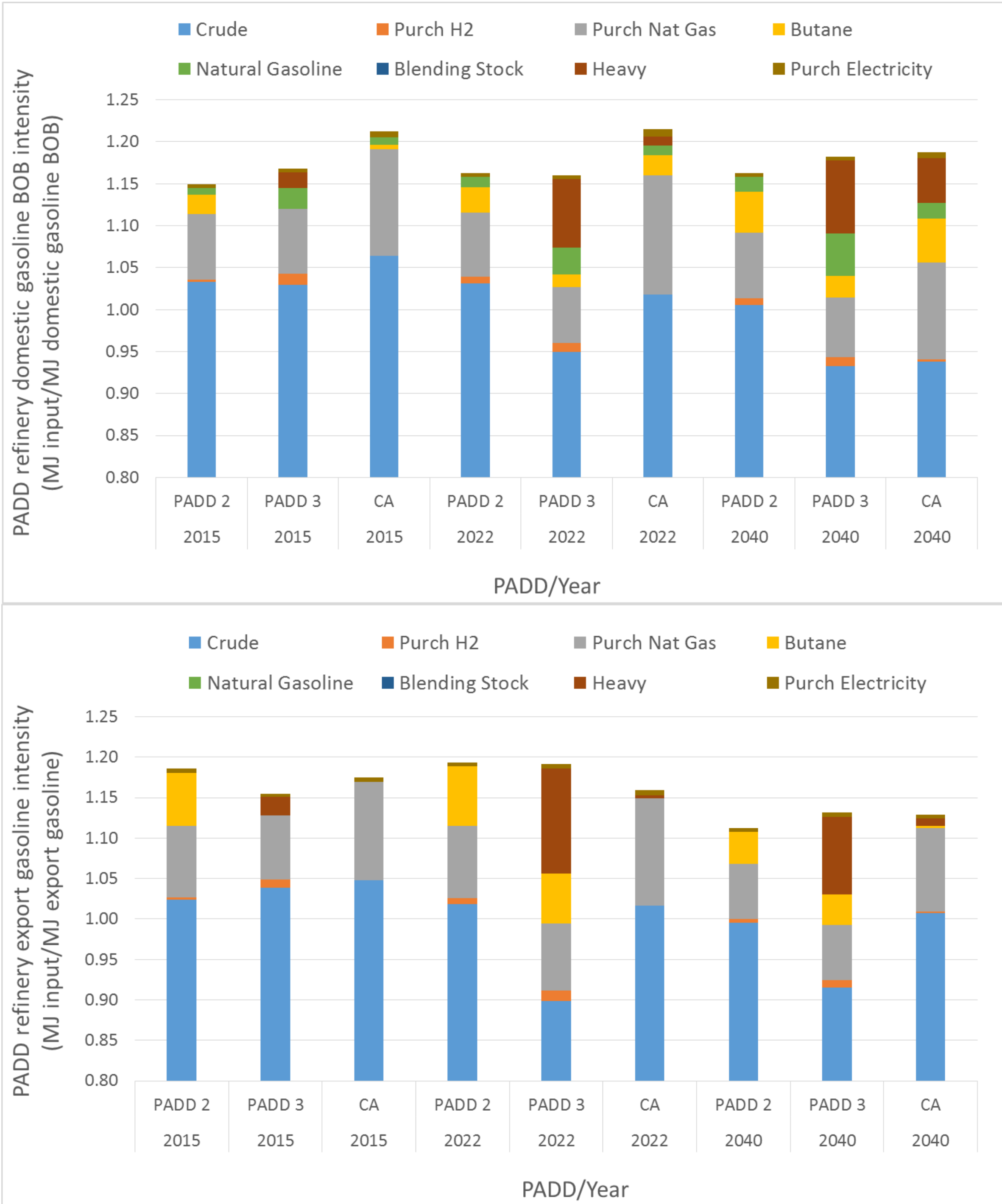


Figure 6-3. Aggregate Refinery Base Case Gasoline BOB Energy Intensity in Three Regions and Three Years

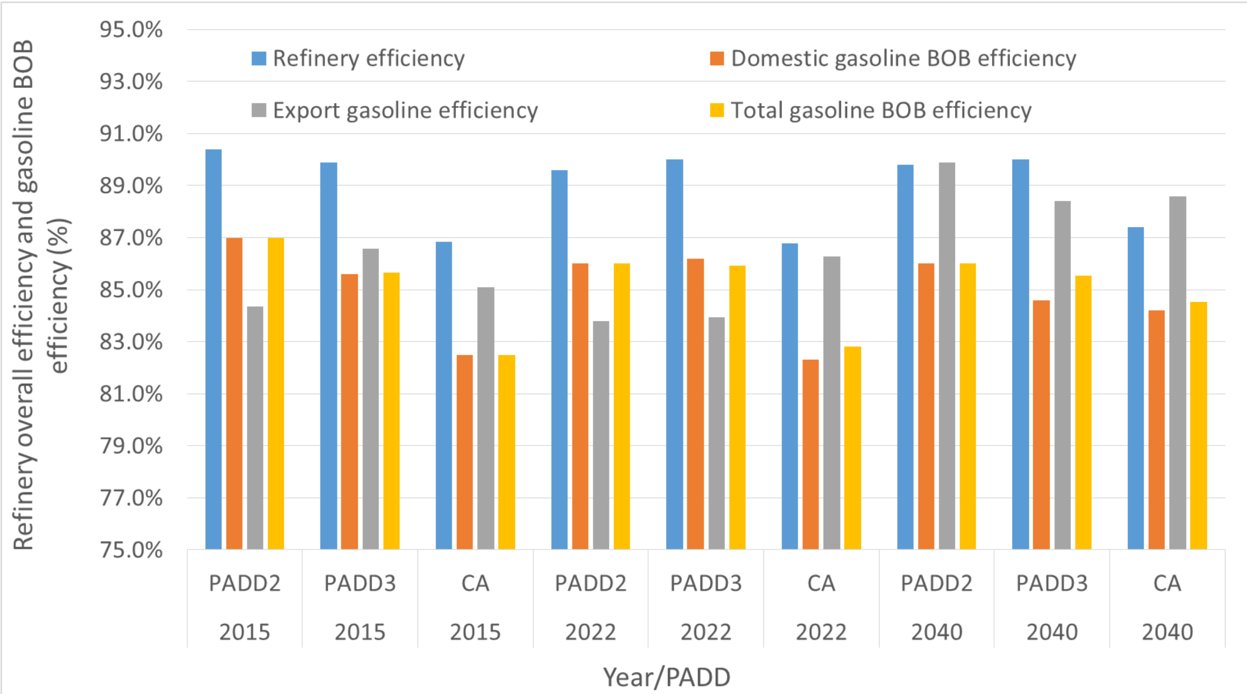


Figure 6-4. Refinery Energy Efficiency and Gasoline BOB Energy Efficiency for Aggregate Refinery Base Cases

Figure 6-4 shows that for all three years studied, CA has much lower efficiency than PADD 2 and PADD 3. This is attributed to higher natural gas usage, primarily for the production of hydrogen via SMR to serve the higher hydrogen demand in CA refineries (the result of processing heavier crude, with API 25), as discussed in the refinery modeling section. From 2015 to 2022 and 2040, the refinery efficiency in PADD 2 decreased due to the increase of natural gas input and purchased hydrogen input, most likely attributable to more use of oil sands. For CA, refinery efficiency in 2040 increased slightly compared with that in 2015 and 2022, due to decreased crude input despite the increased input from heavy feedstock (purchased unfinished oil).

The energy efficiency for each refinery gasoline product is also shown in Figure 6-4. Gasoline efficiency is lower than overall refinery efficiency because gasoline production is more energy intensive than the other refinery production, as it uses more energy intensive units (e.g., reformer, FCC, alkylation). A general conclusion or trend could not be drawn by comparing the efficiency of domestic gasoline and export gasoline, because the components of domestic gasoline and export gasoline vary among the different cases.

6.2.2 Energy Intensity and Efficiency of Aggregate Refineries and for E Set Gasoline BOBs

As in the base case analysis, the overall refinery energy intensity and efficiency for the PADD 3 refinery and CA refinery producing E set fuels were calculated.

6.2.2.1 Energy Intensity of Efficiency of Aggregate Refineries

For each PADD or region refinery in 2022, the variation in energy source distribution used to produce the E set gasoline BOBs is small. It is worth noting that in each PADD/region, the energy usage patterns for E set fuels production are very similar to those of the base case for the PADD 3 refinery and CA refinery in 2022. Consistent with the base cases, the PADD 3 refinery with E set fuels production uses a large amount of heavy oil; in contrast, the CA refinery consumes a large amount of natural gas. See Figure 6-5.

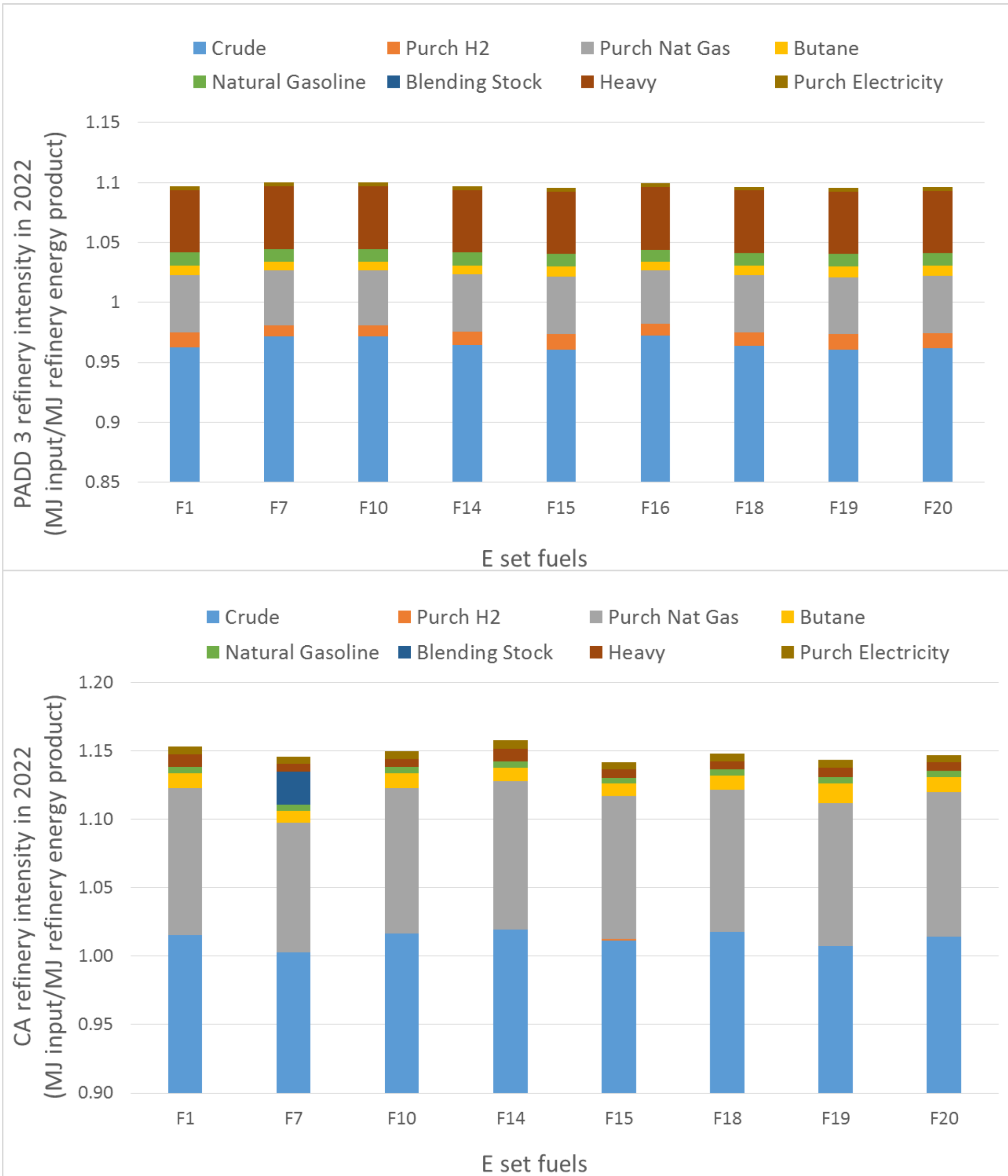


Figure 6-5. Refinery Energy Inputs of PADD 3 and CA Refineries with E Set Fuel Production in 2022

The refinery energy intensities for E set gasoline BOB production in PADD 3 and in CA in 2040 are also very similar to those of the base cases (see Figure 6-6). From 2022 to 2040, the CA refinery shows increased usage of heavy oil coupled with the decreased usage of crude oils.

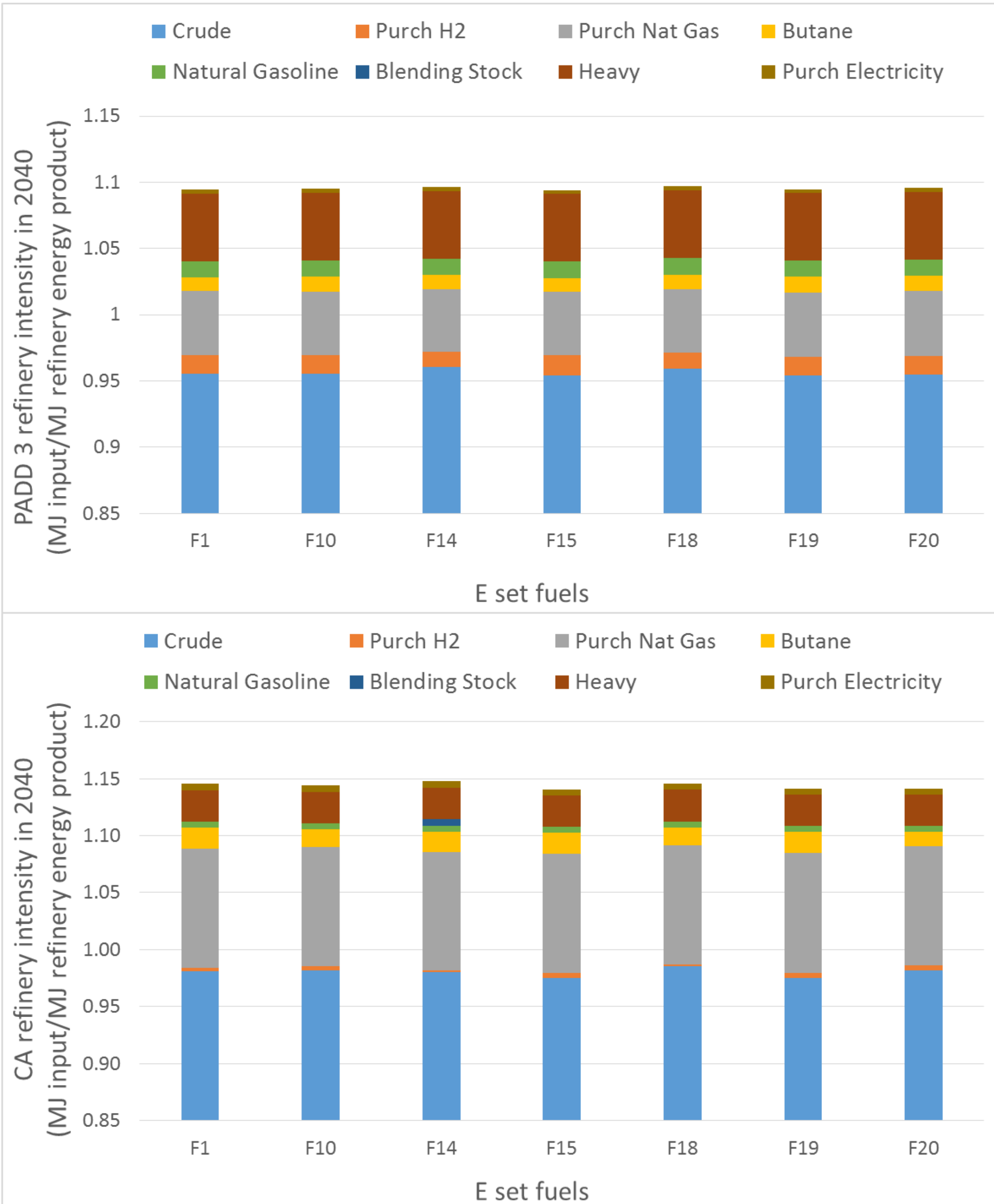


Figure 6-6. Refinery Energy Inputs of PADD 3 Refinery and CA Refinery with E Set Fuel Production in 2040

Overall refinery efficiency was also calculated for aggregate cases with E set fuels production. The results are shown in Figures 6-7 and 6-8 below for 2022 and 2040, respectively.

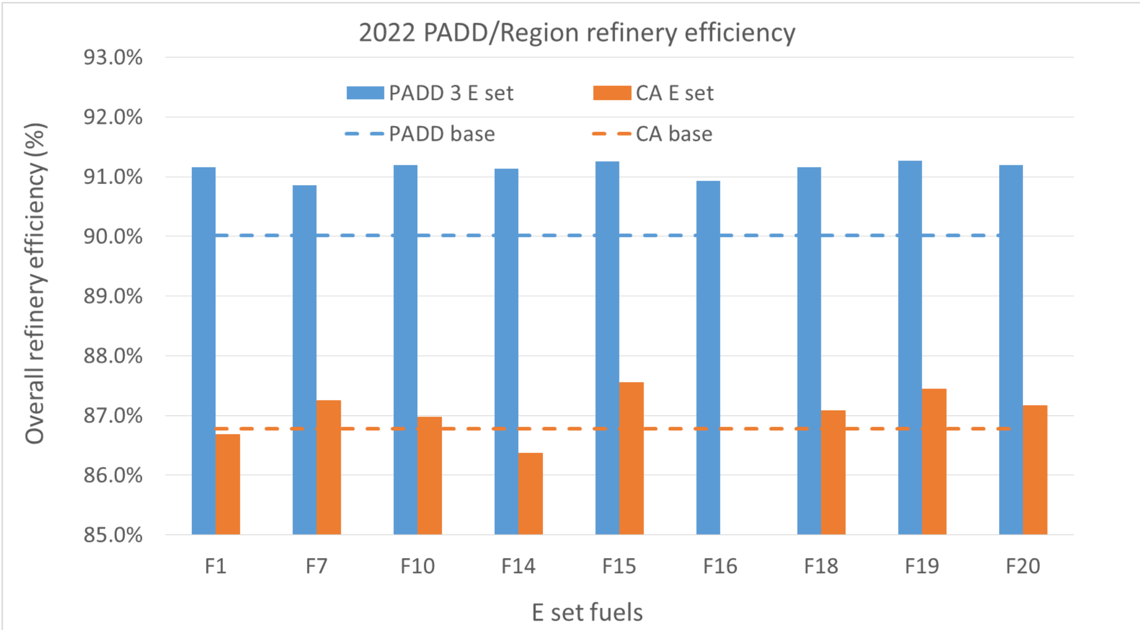


Figure 6-7. PADD Refinery Efficiency in Year 2022 (overall refinery efficiency for all energy products)

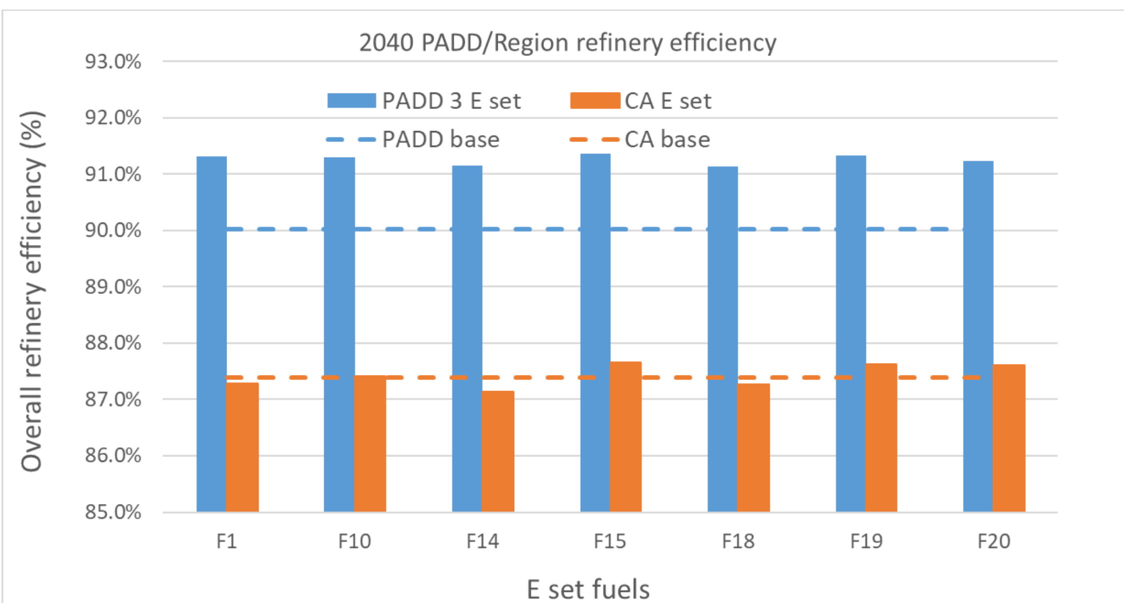


Figure 6-8. PADD 3 and CA Overall Refinery Efficiency in Year 2040 (dotted line are baselines)

In 2022, the LP modeling of Fuel 16 in CA refineries cannot yield a feasible solution (without refinery investment, as discussed earlier). In 2040, LP modeling cannot yield feasible solutions for Fuel 7 and Fuel 16 in either PADD 3 or CA. The refinery efficiencies to produce E set fuels in PADD 3 in 2040 are higher than the base case efficiency, as they are in 2022. Comparing the energy intensities of these E set fuels with that of baselines shows that the E set fuels have less energy input from crude than baselines (resulting in lower energy intensity thus higher efficiency), which is a result of comprehensive refinery re-balance in energy flow, mass flow and operation, to produce gasoline BOB for high octane E set gasolines. It is worth emphasizing that the production of gasoline BOBs are optimized to blend with ethanol to meet the specification/targets of the finished gasoline, but the ethanol is not produced inside refineries, and not included in the refinery efficiency calculation. For CA, in 2040, more refineries show decreased efficiencies (to produce E set fuels) compared with the base case than in 2022, implying that CA refineries encounter more challenges in producing high octane ethanol-blended fuels than PADD 3 refineries do.

6.2.2.2 E Set Gasoline BOB Energy Intensity in Aggregate Refineries

The energy intensity of gasoline (BAU, HOF and export) in PADD 3 in 2022 were analyzed and are shown in Figure 6-9. Variations in gasoline BOB intensity between different E set fuels (BAU, HOF and export) are small. The energy input distribution patterns are different for the BOBs of BAU, HOF and export gasolines.

The results discussed in Section 5 showed that the production of high-octane bio-blended fuels was associated with more gasoline exports. In some cases, the export gasoline from E set fuels production has a higher energy intensity than that of the base cases, indicating the burden shift from domestic E set gasoline to export gasoline. Previous research suggests accounting for the burden shift (which means GHG intensive gasoline streams are shifted from domestic gasoline to export gasoline) by adding the burdens back to domestic gasoline pool, which was adopted here.[5] It is calculated by adding the excess export gasoline intensity to the HOF gasoline intensity after appropriate volume conversion.

The export gasoline burden shift back to the E set fuels produced in aggregate refineries in PADD 3 and CA is shown Table 6-1.

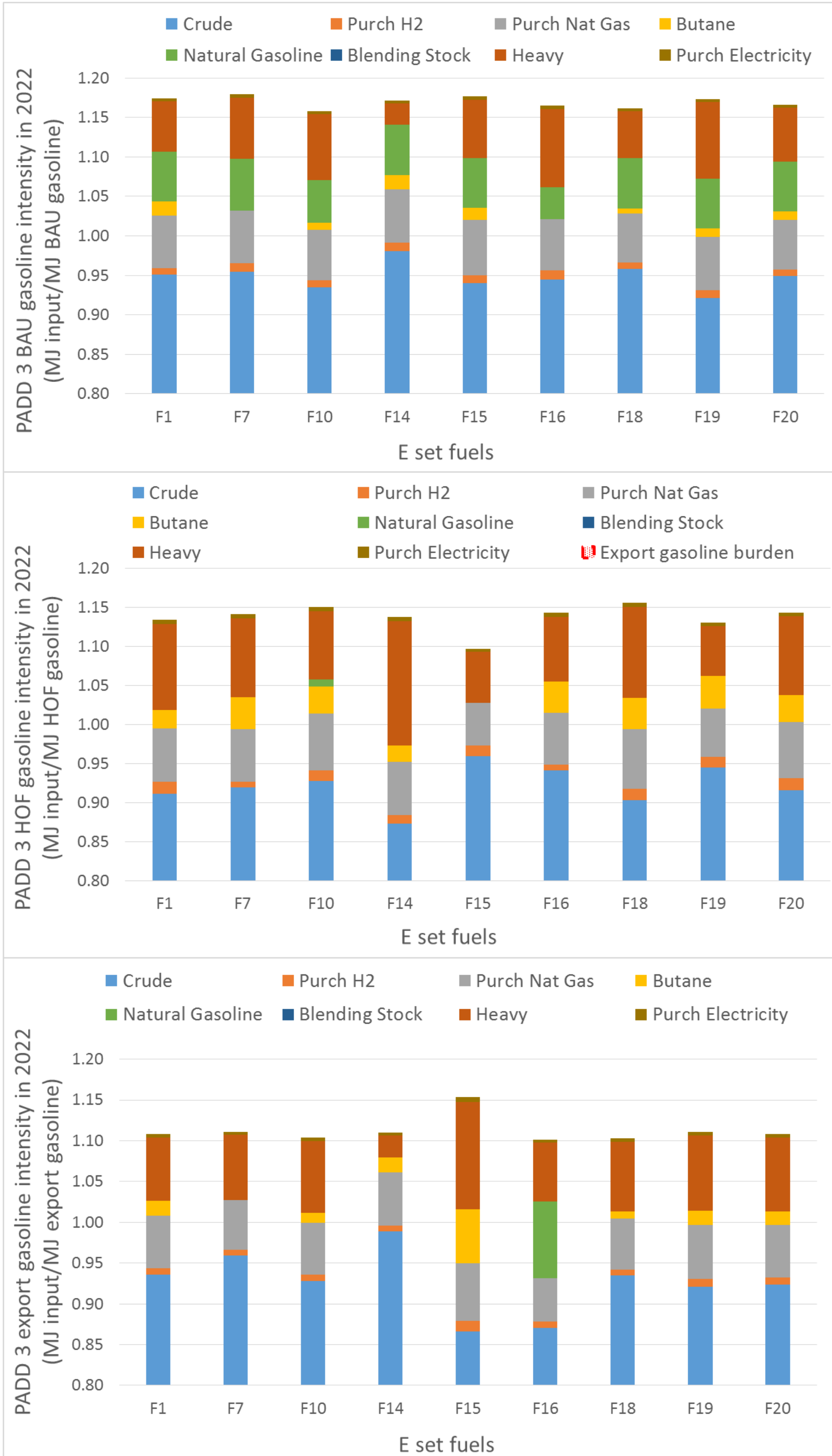


Figure 6-9. The Energy Intensity of E Set Gasoline BOBs Produced in PADD 3 in 2022

Table 6-1. Burden Shift for E Set Fuels (MJ input/MJ gasoline)

Year	2022		2040	
Region	PADD 3	CA	PADD 3	CA
F1	0.000	0.000	0.001	0.001
F7	0.000	0.001	--	--
F10	0.000	0.000	0.000	0.000
F14	0.000	0.000	0.001	0.001
F15	0.000	0.000	0.008	0.008
F16	0.000	--	--	--
F18	0.000	0.000	0.001	0.001
F19	0.000	0.000	0.000	0.000
F20	0.000	0.000	0.000	0.000

For most cases, the burden shift is zero or negligible, as the E set export gasoline has lower intensity than that of the base cases. For those with burden shift, the burden intensity is added to the HOF gasoline production intensity with dashed lines in Figure 6-10 to 6-12 (for some cases it might be too small to notice).

In PADD 3 in 2022, the variations in gasoline intensity for different E set fuels (BAU, HOF and export) are small. The energy input distribution patterns are different for BAU, HOF and export gasolines. The export gasoline burden to HOF for E set fuels in PADD 3 in 2022 is zero.

CA refineries in 2022 use more diversified energy input sources for the production of E set BAU gasoline than for the production of HOF gasolines and export gasolines. See Figure 6-10.

For CA refineries in 2022, the production of E set BAU gasolines have more diversified energy input sources relative to the production of HOF gasolines and export gasolines. For almost all E set fuels produced in CA in 2022, the export gasoline burden to HOF is negligible. In CA refinery, the blendstock refers to alkylate purchase, assuming that alkylate (and other blendstocks) are traded blendstocks.

For a PADD 3 refinery in 2040, the differences in energy input distribution patterns among various E set gasolines are more pronounced, compared with those of the PADD 3 refinery in 2022. The lower energy intensity of BAU gasoline for Fuel 14 and Fuel 18 (compared with the other E set fuels) is coupled with the higher energy intensity of their export gasoline counterpart. For these three fuels, especially for Fuel 15, the export gasoline burden is noticeable. See Figure 6-11.

For the CA refinery in 2040, E set BAU gasoline has higher energy intensity than its counterpart export gasoline. The former has energy inputs from various sources, dominated by crude oil, natural gas and heavy oil. The latter uses fewer sources of energy and mainly gets energy input from crude oils and natural gas. As in PADD 3 in 2040, Fuel 15 HOF fuel has a noticeable export gasoline burden. See Figure 6-12.

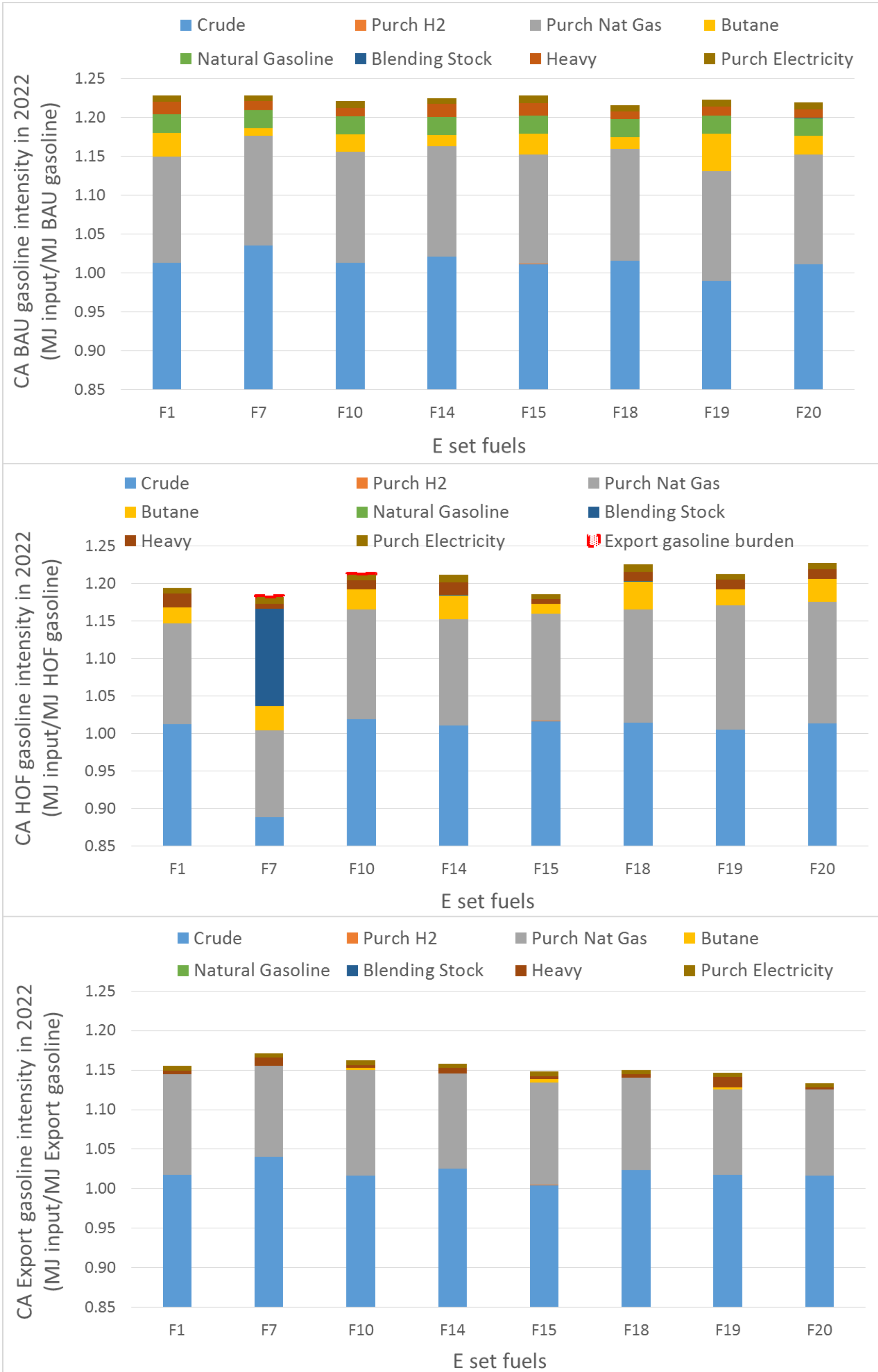


Figure 6-10. Energy Intensity of E Set Gasolines Produced in CA in 2022

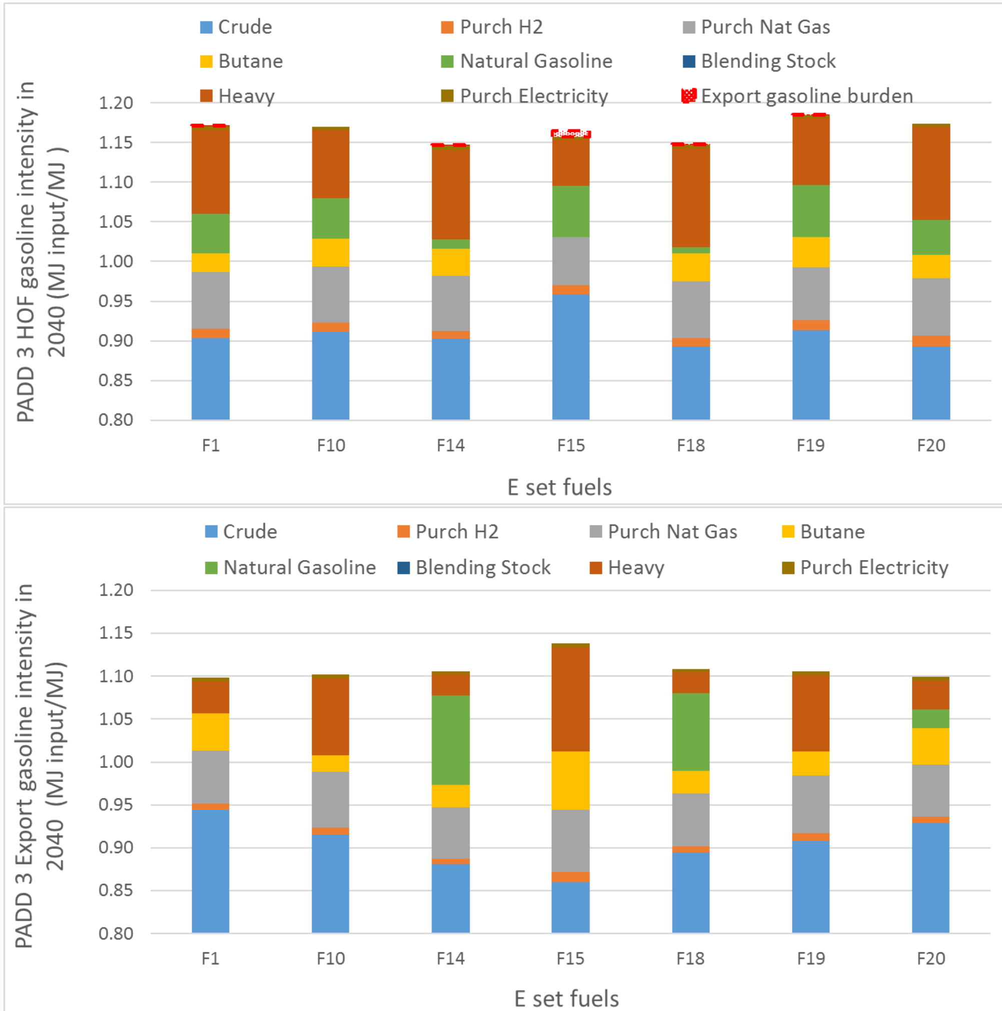


Figure 6-11. The Energy Intensity of E Set Gasolines Produced in PADD 3 in 2040

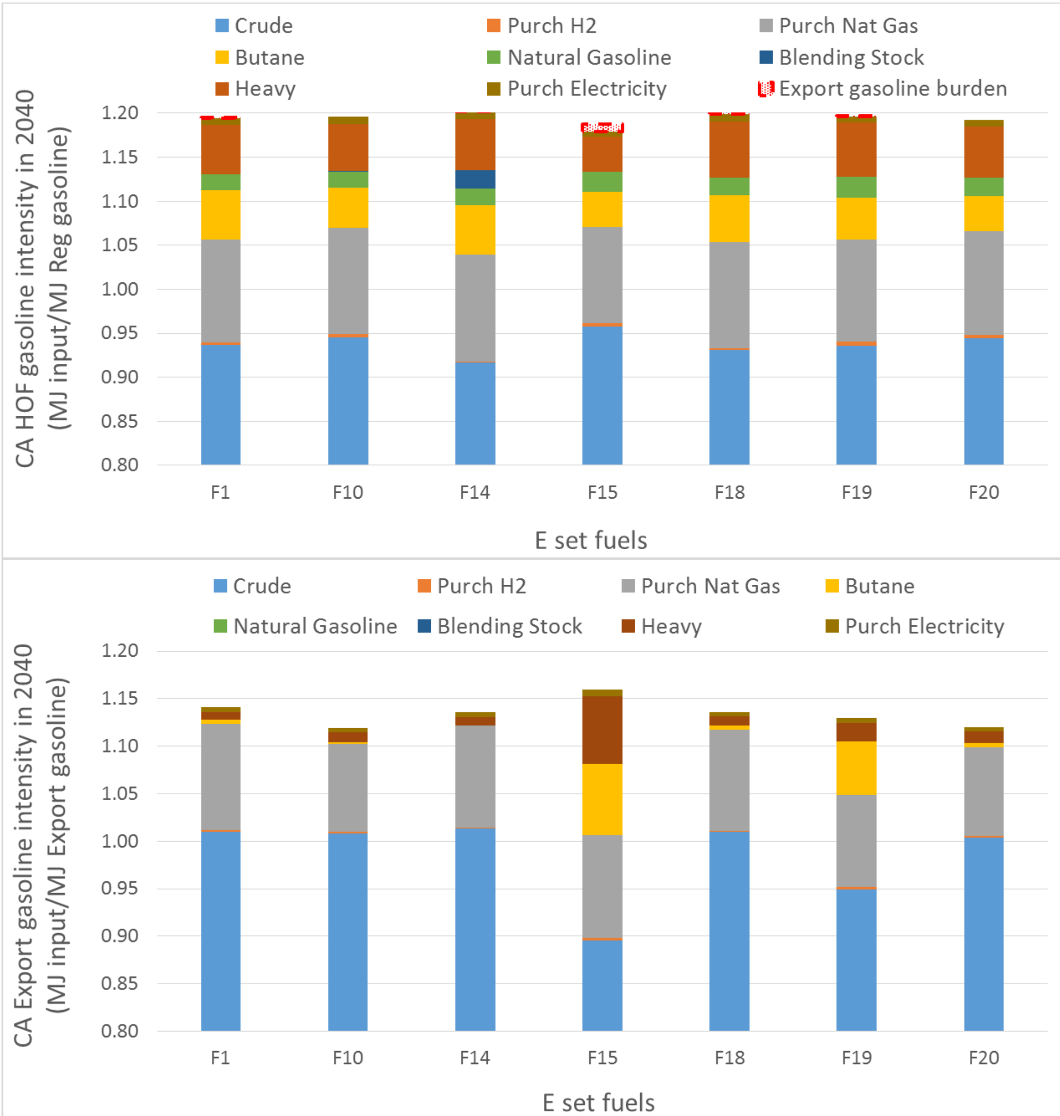


Figure 6-12. Energy Intensity of E Set Gasolines Produced in CA in 2040

6.2.2.3 E Set Gasoline BOB Production Efficiency in Aggregate Refineries

The gasoline production efficiency of various E set fuels produced in PADD 3 and CA refineries, for both domestic and export gasoline, is shown in Figure 6-13.

As expected, the gasoline BOBs produced in CA have lower efficiencies than those produced in PADD 3. For CA, the gasoline BOBs produced in 2040 have higher efficiencies than those produced in 2022; however, this trend is not observed for PADD 3. The reasons for this trend could be complex, depending on crude slate change, refinery operation and practice in response to crude change, the lower G/D ratio in 2040, resultant fuel components, and/or a gasoline and diesel export increase that shifts allocation of energy use and emission burdens among different refinery products. For most cases of E set gasolines produced in PADD 3 and CA, the export gasolines have higher efficiencies than domestic gasolines.

Figure 6-13. Refinery Production Efficiency of Domestic Gasoline BOB and Exported Gasoline of E Set Fuels in PADD 3 and CA in 2022 and 2040

The efficiencies of BAU gasoline BOB and HOF gasoline BOB of E set gasolines produced in PADD 3 and CA in 2022 are shown in Figure 6-14. For E set fuels produced in PADD 3, all HOF gasoline BOB have higher efficiencies than BAU gasoline BOB, while for E set fuels produced in CA, most HOF gasoline BOB have higher efficiencies than BAU gasoline BOB except for Fuel 18 and Fuel 20 (Figure 6-14). The different gasoline efficiency is a result of different energy inputs for the gasoline production, as shown in detail in Figures 6-9 through 6-10. It is interesting to observe that although HOF has higher octane demand than BAU gasoline, the production burden (more energy input than baselines) is not necessarily directed to the HOF pool. The response to the high octane demand of the HOF pool does not come from a single unit or stream but requires a comprehensive, holistic re-balance of energy flow and mass flow to reach profit maximization. For example, in PADD 3 in 2040, domestic F19 (30% EtOH, 101RON) has lower efficiency than F15 (30% EtOH, 97 RON), attributed to the higher energy input from butane and heavy oil for F19 production, resulting in higher energy intensity for F19 production. In contrast, domestic F18 (20% EtOH, 101 RON) has higher production efficiency than F20 (20% EtOH, 97 RON), because F18 has less energy input from natural gasoline, resulting in lower energy intensity for gasoline production. Again, these refinery inputs and operation are optimized to maximize refinery profit, not to maximize efficiency.

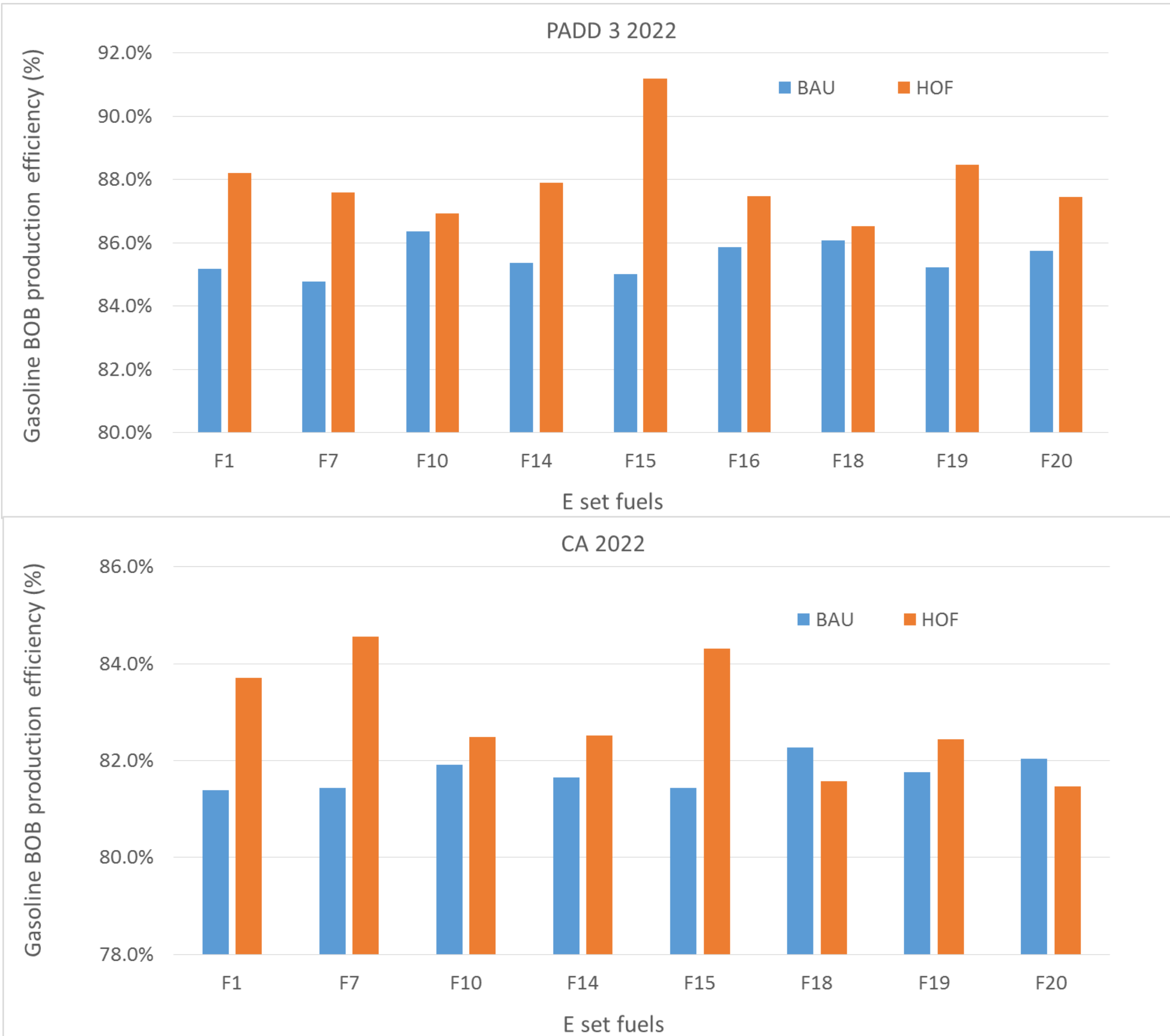


Figure 6-14. BAU and HOF Gasoline BOB Efficiency of E Set Fuels Produced in PADD 3 and CA in 2022

6.2.3 Energy Intensity and Efficiency of Configuration Refineries

The energy intensity and efficiency for overall configuration refineries with E set fuels production were studied and are compared below, along with the calculation of energy intensity and efficiency for gasoline production specifically.

6.2.3.1 Overall Configuration Refinery Base Cases Efficiency and Intensity

The overall configuration refinery base cases energy intensity are shown in Figure 6-15.

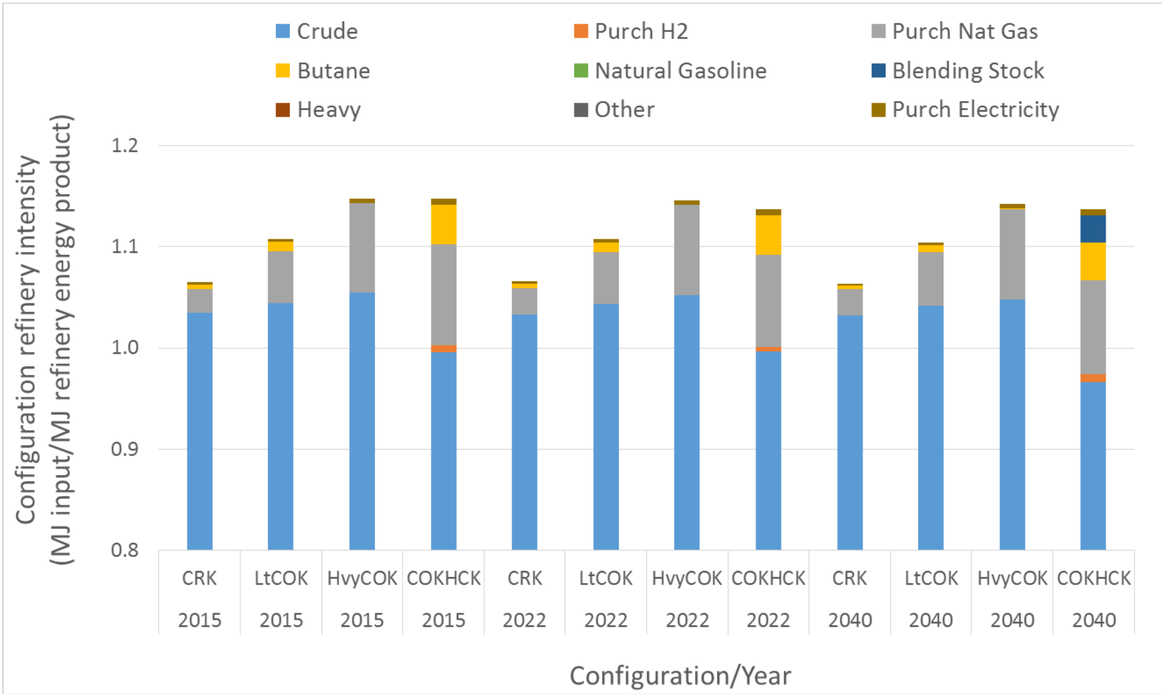


Figure 6-15. Overall Refinery Energy Intensity of Configuration Refinery Base Cases

In each year studied, the refinery energy intensity of the four configuration models varies significantly. As expected, the more complex refinery configurations, HvyCOK and COKHCK, require much higher energy input per MJ of refinery energy products. Most of the energy input is from natural gas, consistent with the increased hydrogen supply for the HvyCOK and COKHCK configuration refineries. Compared with the other configurations in PADD 3, the COKHCK configuration in CA has noticeable input from butane and blendstock. This might be related to the aromatic constraint in CA, which requires high-octane blending streams in place of reformate. For each configuration refinery, the refinery intensity decreases slightly from 2015 to 2022 and 2022 to 2040. This might be a result of decreasing G/D ratio. Previous research has shown that gasoline production is more energy intensive than other refinery products (e.g., diesel fuel and jet fuel) [29]. Thus in 2022 and 2040, the lower gasoline but higher diesel production will shift refinery operations to diesel-oriented units, which are commonly less energy intensive than gasoline-oriented units.

6.2.3.2 Configuration Refinery Base Cases Gasoline Production Efficiency and Intensity

The gasoline production energy intensity in configuration refineries are shown in Figure 6-16.

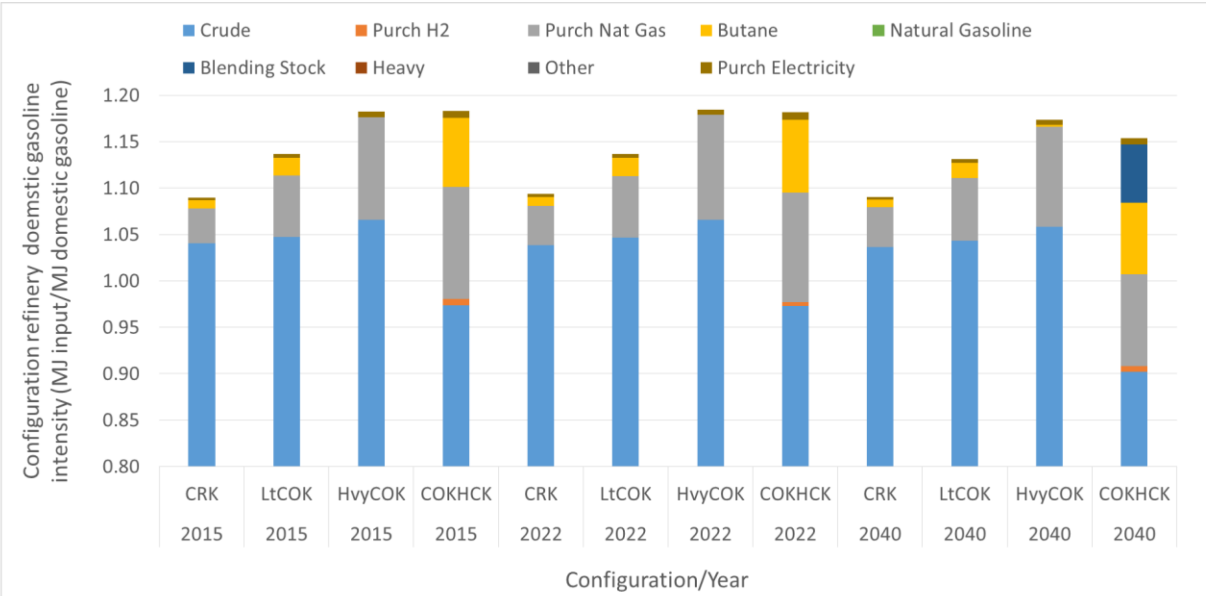


Figure 6-16. Configuration Refinery Base Cases Gasoline Production Energy Intensity

Like overall refinery intensity, the energy intensity for gasoline production in the configuration refinery base cases increases with increasing refinery complexity. For each case, gasoline production intensity has lower natural gas input compared with overall refinery intensity. The COKHCK refinery configuration is distinguished from the others by higher butane use (for alkylate production).

The efficiencies of the configuration refineries producing base case E10 gasolines, for both overall refinery efficiency and gasoline production, are shown in Figure 6-17.

The simpler CRK has the highest efficiency, and the efficiency decreases for more complex configurations. There are small changes in efficiency among the studied years. Overall, gasoline production efficiency is lower than overall refinery efficiency because the gasoline streams are often sourced from complicated and energy intensive units via multiple steps of conversion [29]. In contrast, some other refinery products, such as jet fuel, are produced through fewer conversion steps and/or sourced from less energy intensive units and so have higher production efficiency.

<u>6.2.4 WTP Analysis of Configuration Refineries with E Set Fuel Production</u>

The E set fuels produced in configuration refineries were studied with the same approaches used for fuels produced in aggregate refineries.

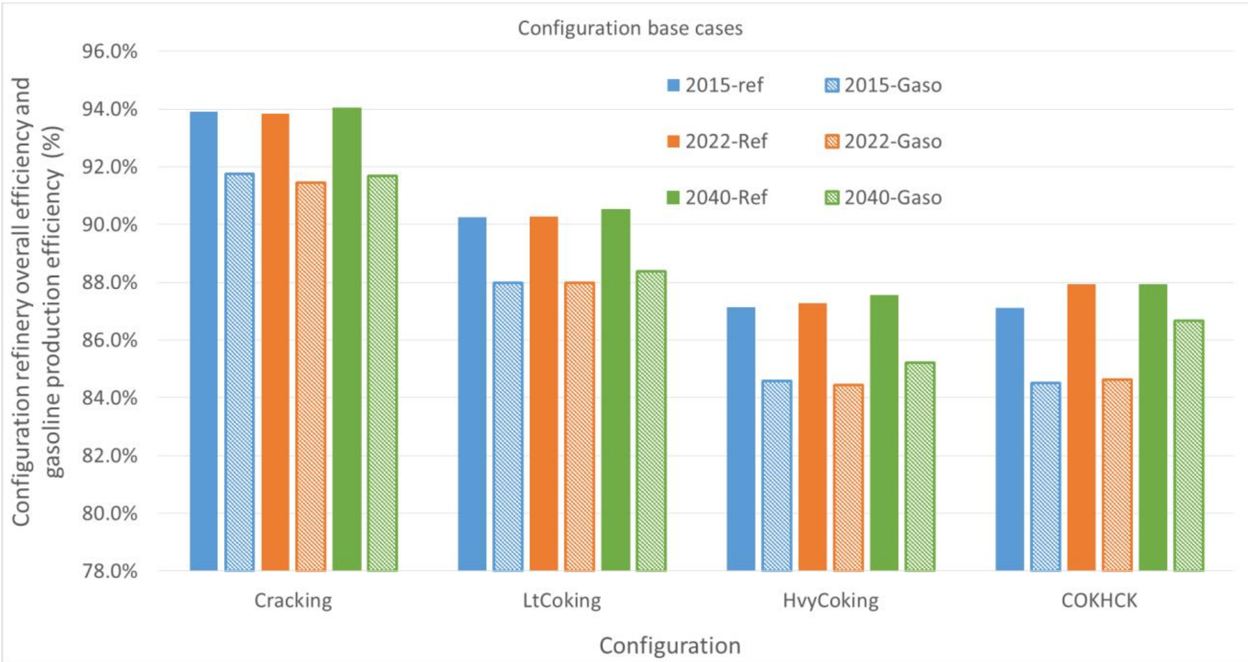


Figure 6-17. Efficiencies of Configuration Refineries to Produce Base Case E10 Gasolines

6.2.4.1 Overall Refinery Intensity and Energy Efficiency of Configuration Refineries with E Set Fuel Production

The energy intensity of configuration refineries with E set fuels production in 2022 is shown in Figure 6-18. With increasing refinery complexity, the overall refinery intensity increases, largely because of the increase in natural gas input, which is driven by increased hydrogen demand, as shown in the refinery analysis section. Compared with the CRK, LtCOK, and HvyCO configurations, the COKHCK configuration has much higher butane input. This butane input might contribute to alkylate production, as the E set gasoline in COKHCK configuration does not show a high butane component, but rather a higher alkylate component compared with the gasoline produced in other configurations.

In 2040, the natural gas input in complex configurations (HvyCOK, COKHCK) is much higher than in less complex configurations (HCK, LtCOK). Compared with the CRK, LtCOK, and HvyCOK configurations, the COKHCK configuration adds “purchased” hydrogen to the large natural gas input from internal hydrogen production. The COKHCK configuration in 2040 is also unique in having some blend stock input, likely for helping boost gasoline octane numbers, compensating for the octane deficit caused by reformate constraints. See Figure 6-19.

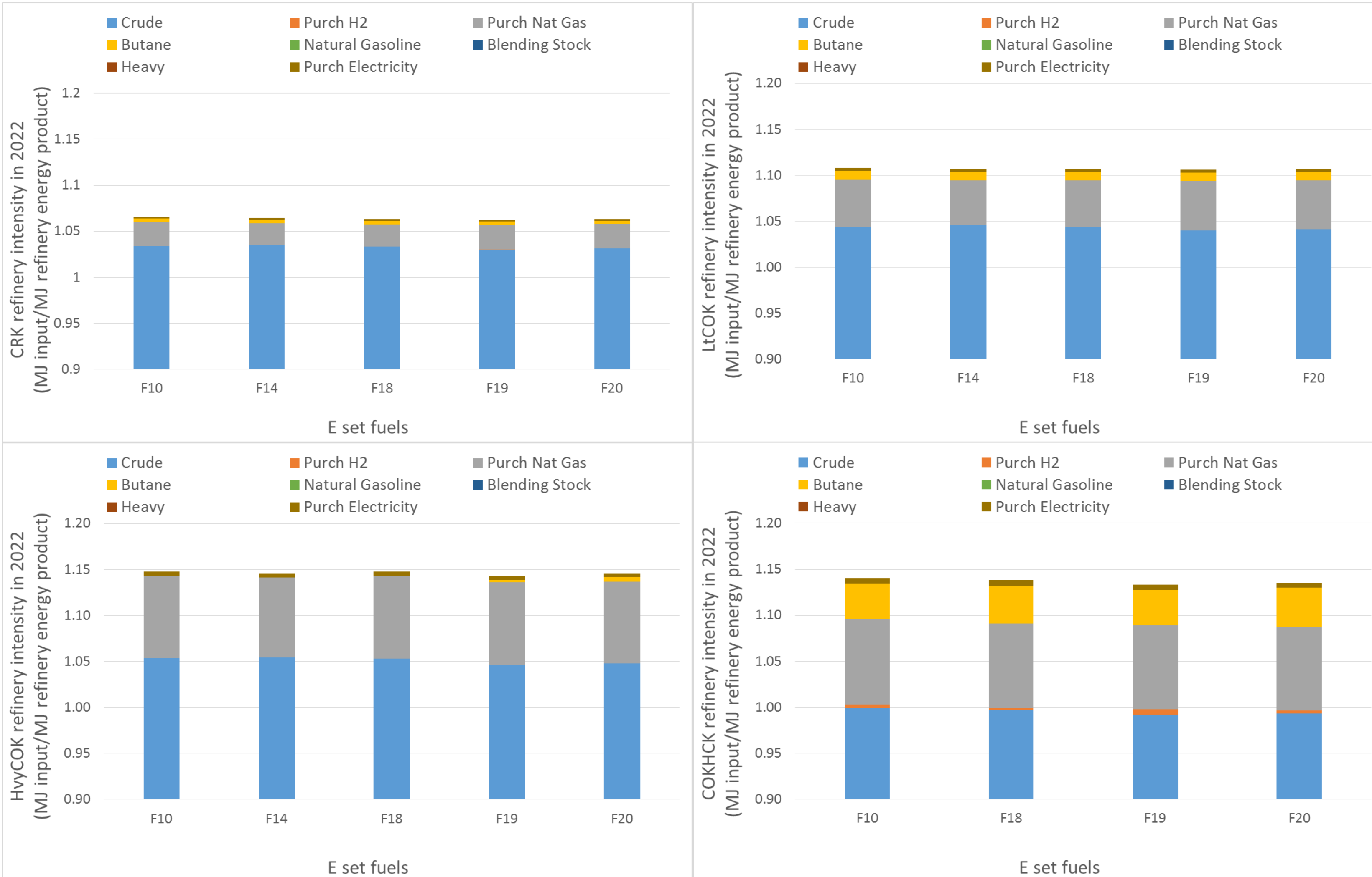


Figure 6-18. Overall Energy Intensity of Configuration Refineries with E Set Fuel Production in 2022

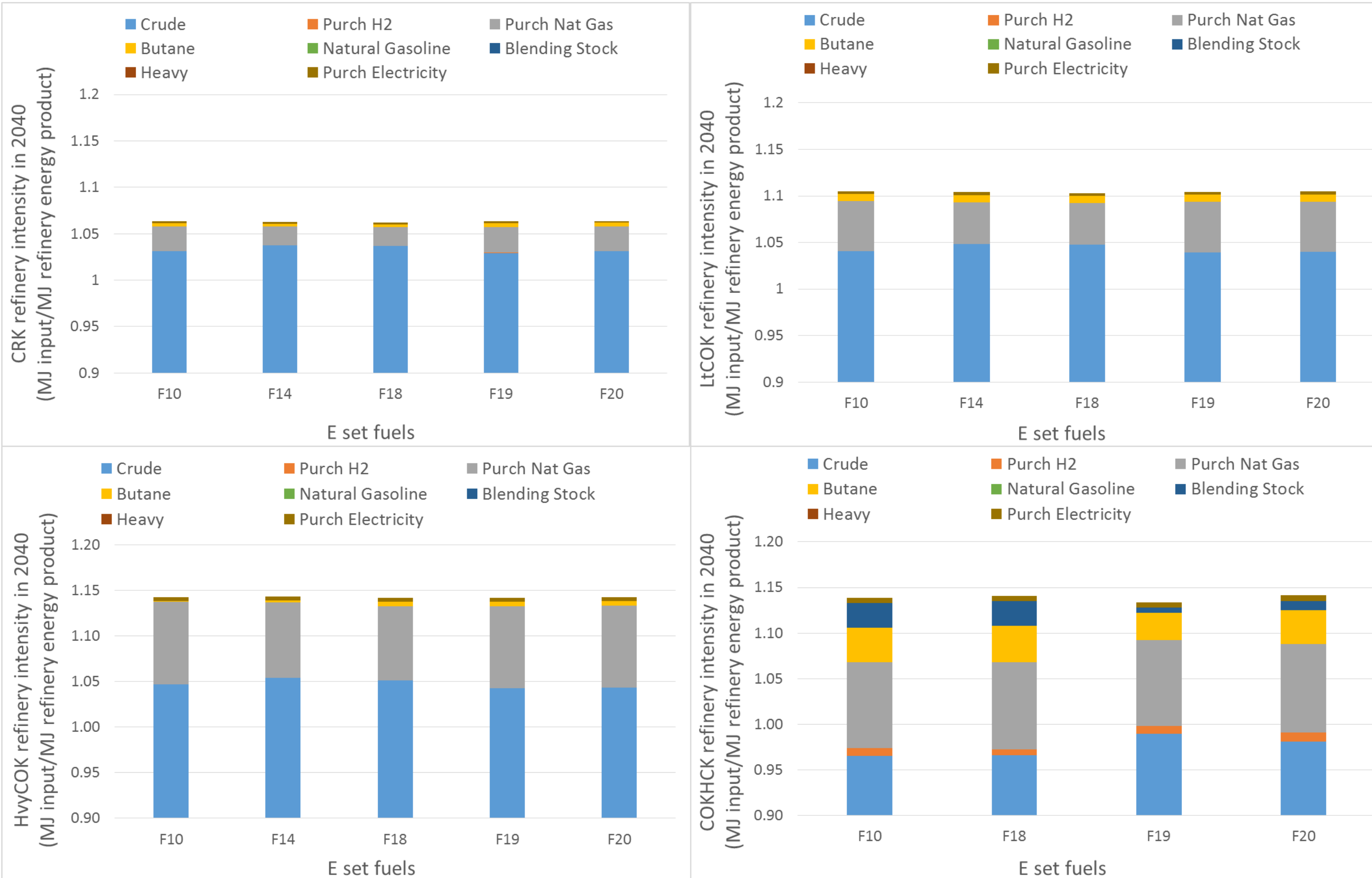


Figure 6-19. Overall Energy Intensity of Configuration Refineries with E Set Fuel Production in 2040

Taking the reciprocals of the energy intensity numbers provides the refinery efficiencies. The results are shown in Figure 6-20.

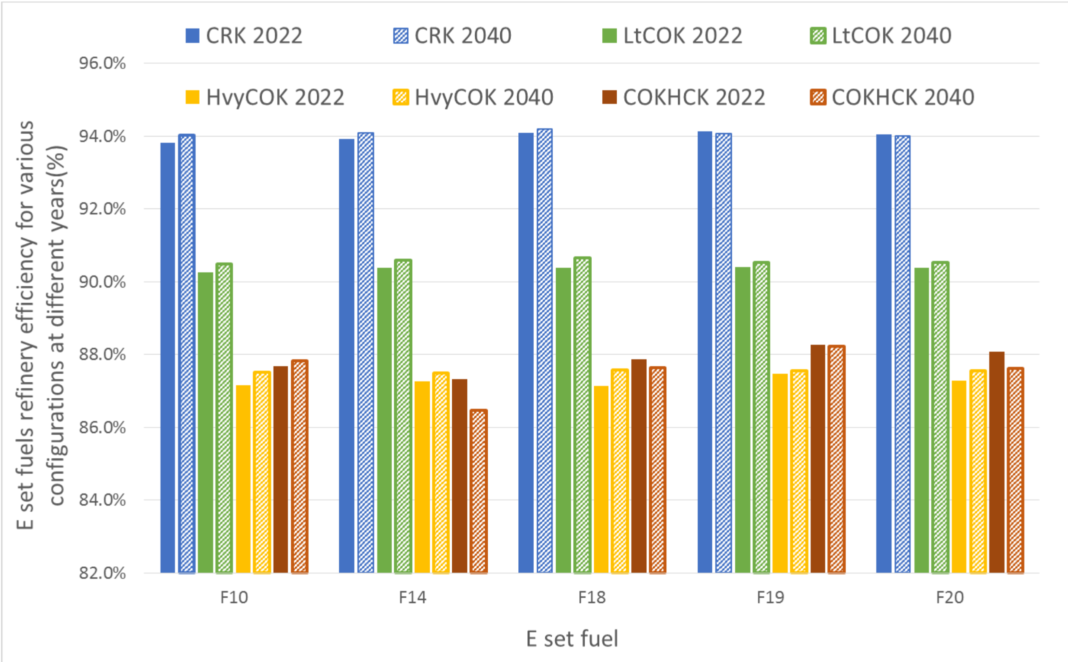


Figure 6-20. Overall Refinery Efficiency of Various Configurations with E Set Fuel Production

The overall configuration refinery efficiencies for production of E set gasoline and other energy products are in line with the base cases and are strongly dependent on configuration. The changes among different fuels are relatively minor. For all configurations, the changes in refinery efficiencies from 2022 to 2040 are minor as well.

6.2.4.2 Gasoline Production Energy Intensity and Efficiency of Configuration Refineries with E Set Fuel Production

The energy intensities of E set gasoline production in configuration refineries were calculated and are shown in Figures 6-21, 6-22, and 6-23. For 2022, energy intensities for BAU gasoline and HOF gasoline are shown, and for 2040, only the intensities of HOF E set gasolines are shown, given its 100% share.

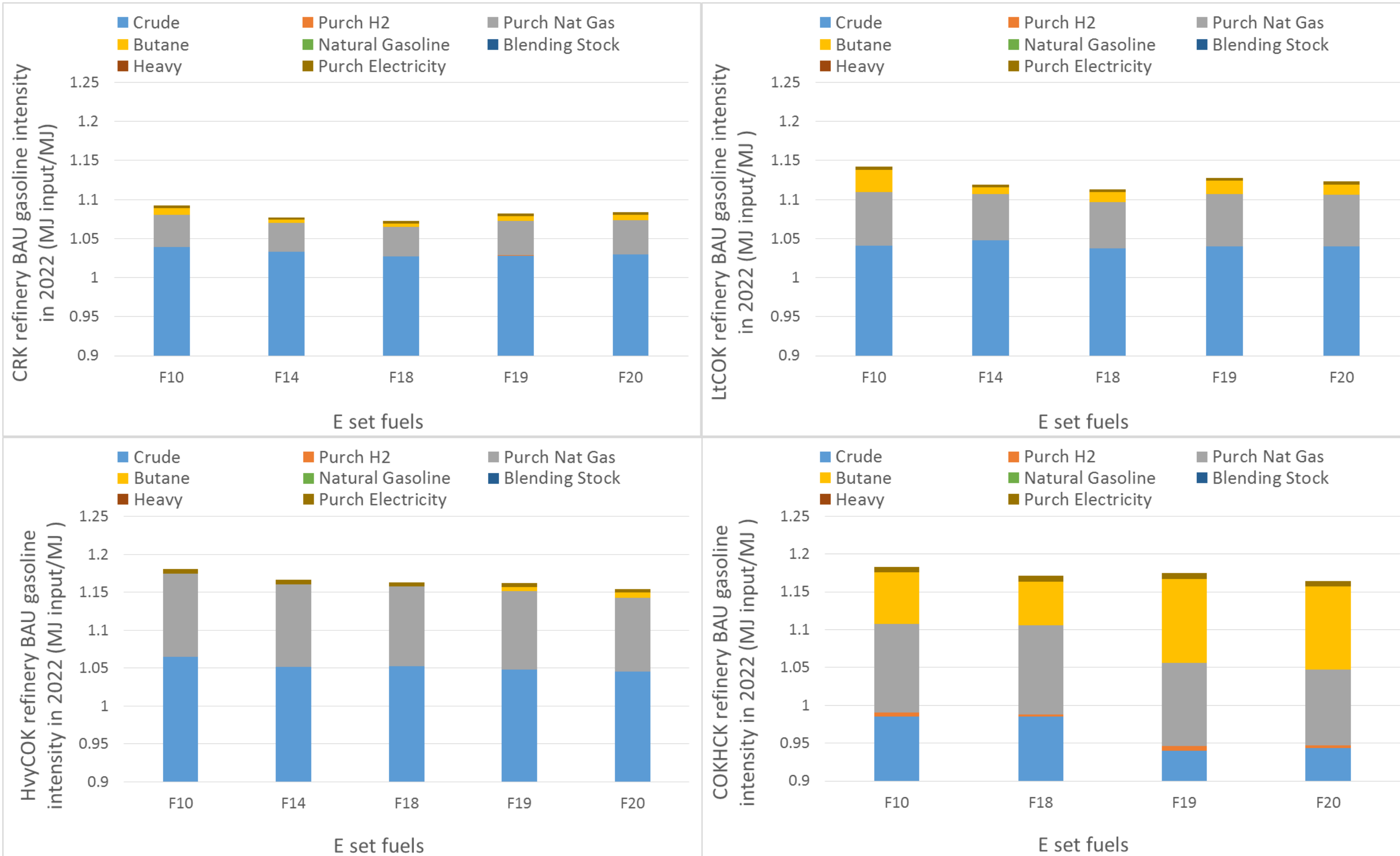


Figure 6-21. BAU Energy Intensities of E Set Gasoline Production in Configuration Refineries in 2022

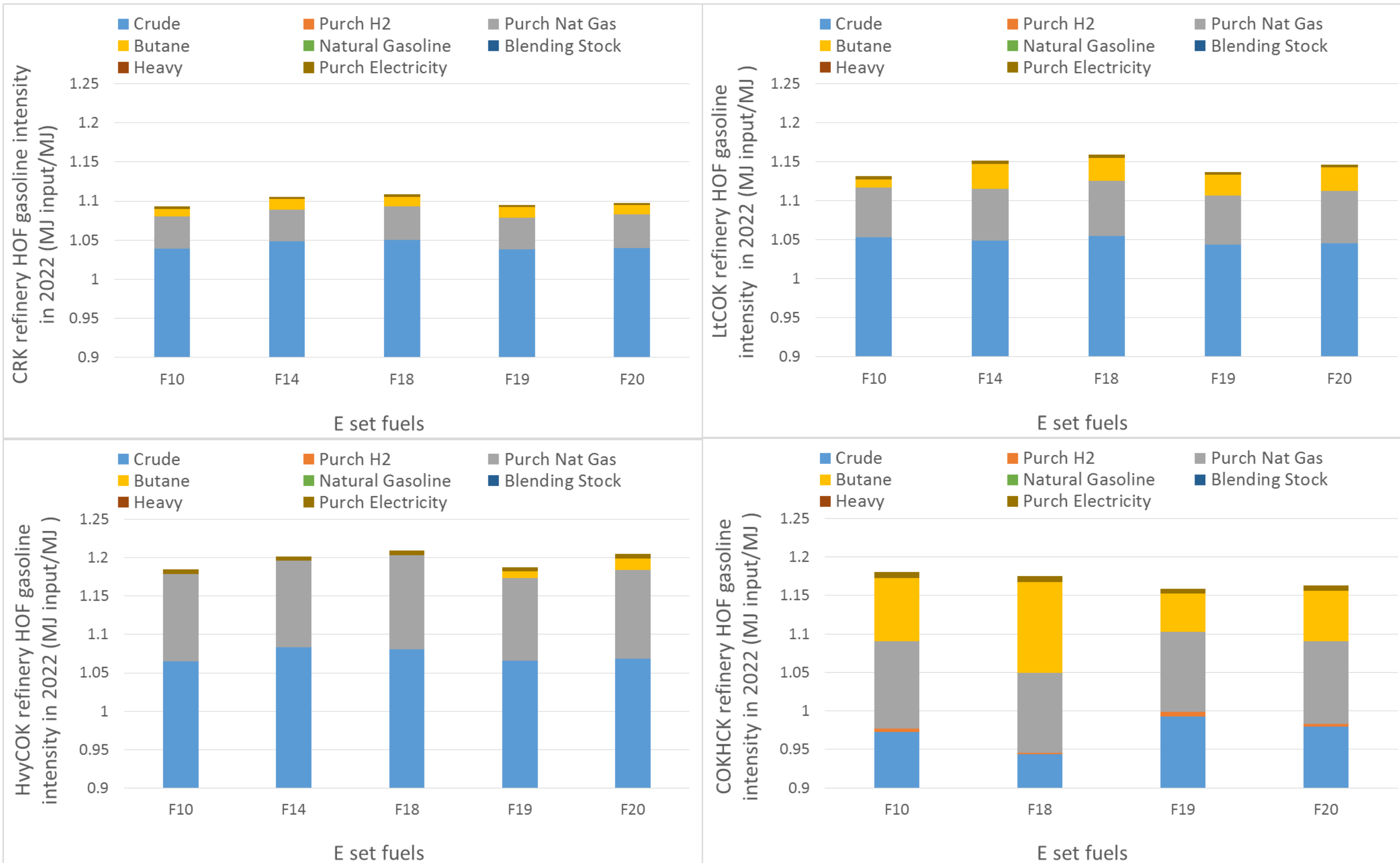


Figure 6-22. HOF Energy Intensities of E Set Gasoline Production in Configuration Refineries in 2022

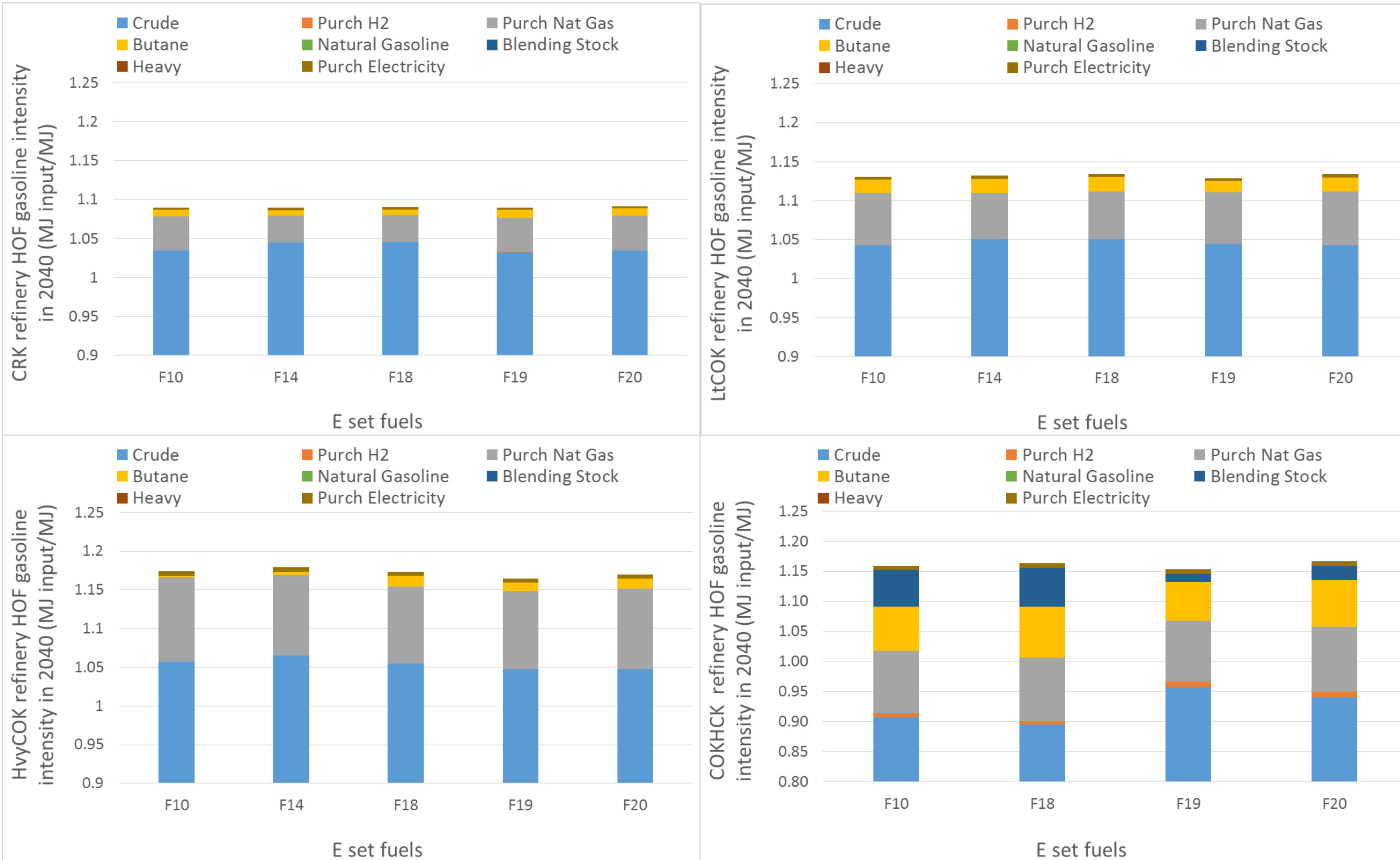


Figure 6-23. HOF Energy Intensities of E Set Gasoline Production in Configuration Refineries in 2040

From 2022 to 2040, the gasoline intensity changes for CRK, LtCOK, and HvyCOK configurations are insignificant. However, there is a noticeable change in the energy input distribution of the COKHCK configuration with the addition of a blending stock (alkylate) in 2040, this is determined by LP modeling for profit maximization. This is consistent with the overall refinery intensity of the COKHCK configuration.

With increasing refinery complexity, the overall gasoline intensity for both BAU and HOF increases, and the intensity increase is mainly because of the increased natural gas input, mostly for hydrogen production. Generally, the more complex refinery strives to transforms heavy bottoms of crude oils into lighter and more valuable products (e.g., gasoline and diesel), thus a large amount of hydrogen needs to be injected to increase H/C ratios. For all configuration refineries, the Fuel 19 gasoline set has the lowest energy intensity, most likely because its 30% ethanol blending eases the refinery challenge to produce high-octane BOBs. The gasoline intensities for export gasoline are not shown here, as the export amount is minimal for each E set case, accounting for only 0.5%–4% of the total refinery BOB production.

The efficiencies for combined BAU and HOF gasoline were also calculated and are compared in Figure 6-24.

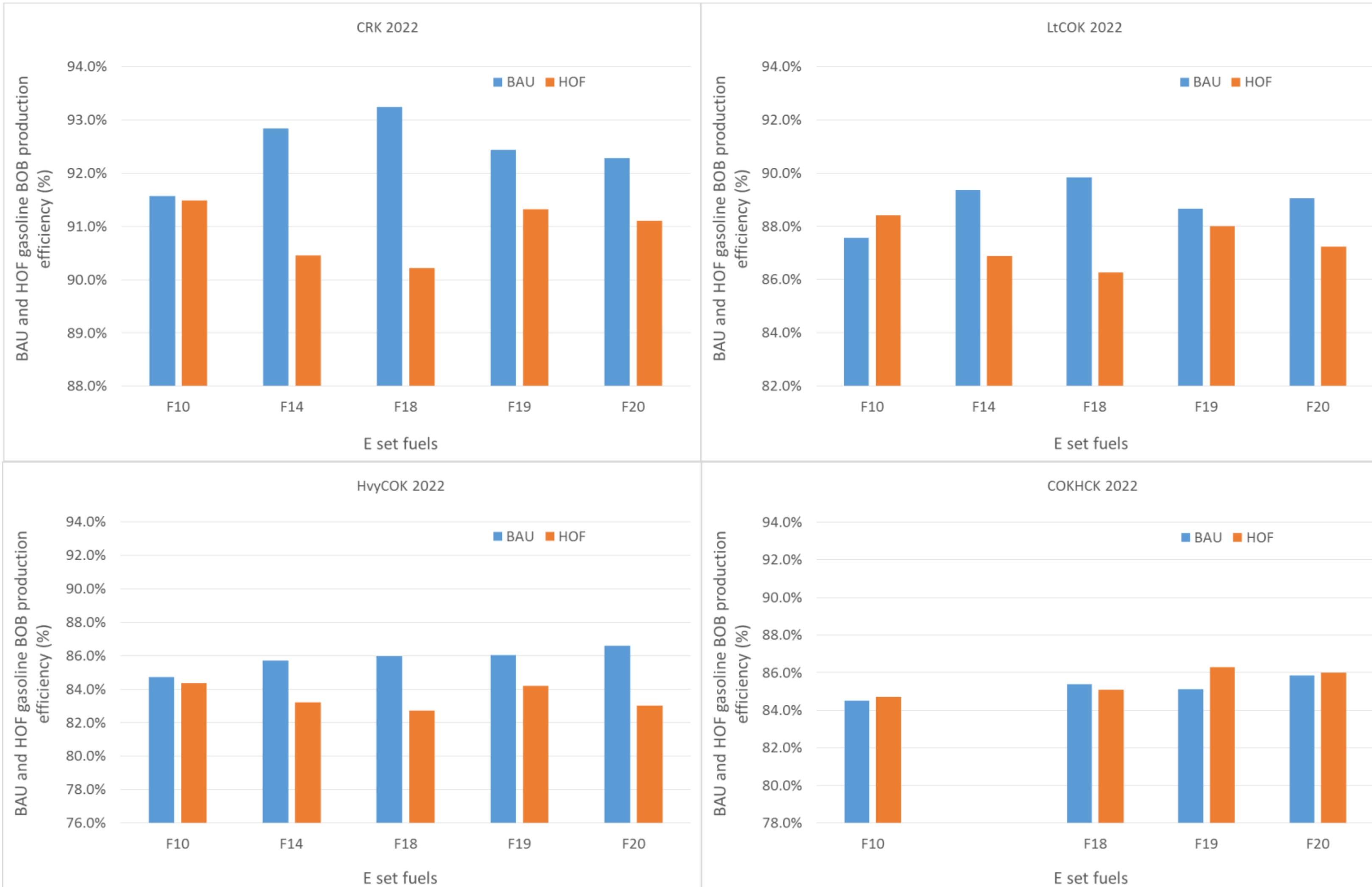


Figure 6-24. E Set Gasoline Production Efficiency (BAU and HOF) for Various Refinery Configurations in 2022

In 2022, the energy intensities for producing E set BAU and HOF gasoline fuels are different for each E set fuel, consistent with the different components of the BAU gasoline and HOF gasolines.

A comparison of domestic gasoline efficiencies produced in different configuration refineries in 2022 and 2040 is shown in Figure 6-25. In 2040, all domestic gasolines are HOF gasolines.

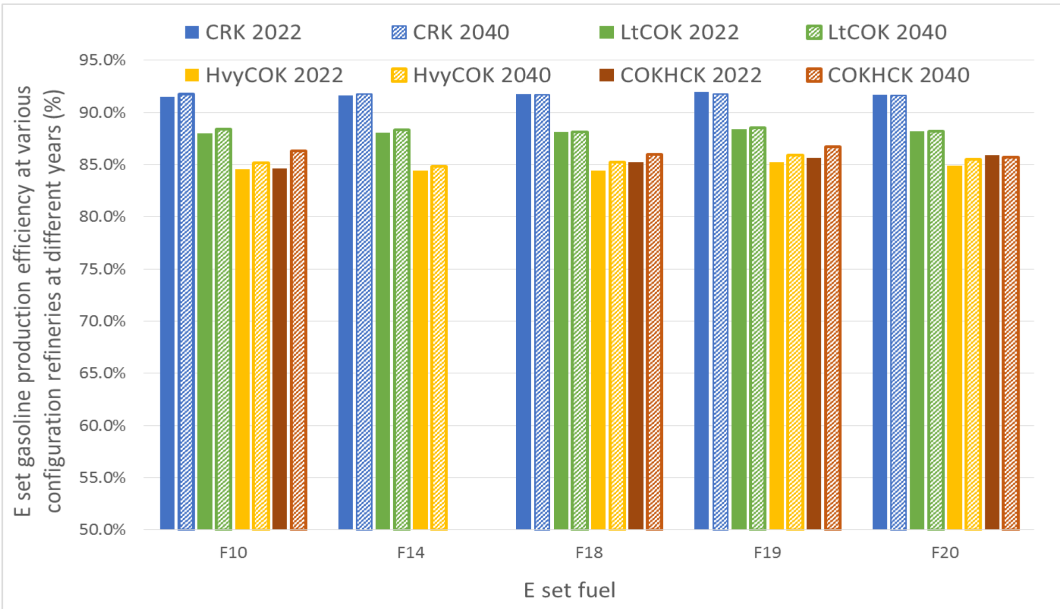


Figure 6-25. Gasoline Production Efficiency (domestic gasoline, including BAU and HOF) for Various Configuration Refineries Producing E Set Fuels

From 2022 to 2040, domestic gasoline production efficiencies increase in most cases. This might be caused by the G/D decrease from 2022 to 2040, resulting in an overall refinery energy input decrease because of an operations shift to less intensive diesel-oriented units, which in turn results in less energy allocation to the gasoline pool.

6.3 BR Set Fuels—Energy Intensity and Efficiency for Overall Refinery and for Gasoline BOB Production

Similar with the cases for E set gasolines, the energy intensity and efficiency analyses for BR set gasolines only account for the energy uses for the gasoline BOB production inside refineries as BR stream is not produced but only blended in refineries.

6.3.1 WTP Analysis of Aggregate Refineries with BR Set Fuels Production

As shown in the refinery analysis section, LP modeling of BR set fuels production is challenging, with only a few feasible solutions. Using toluene as a surrogate for the bioreformate blendstock (BR-T set fuels) allowed for feasible solutions for a few additional cases. It is because compared to bioreformate toluene has similar high RON, but lower boiling point, which can avoid hitting T90 specification. We examined refinery energy use and WTP GHG emissions with these BR/BR-T fuels.

6.3.1.1 Overall Refinery Intensity and Efficiency of Aggregate Refineries with BR Set Fuels Production

In 2022, within each PADD, variations in energy intensity and input distribution among the BR/BR-T fuels are relative small (Figure 6-26). A PADD 2 refinery with BR/BR-T fuels production has energy inputs mainly from natural gas and butane, in addition to the major input from crude oil. In contrast, the PADD 3 refinery has a lower energy share from crude input compared with the PADD 2 refinery, and it has an additional sizeable energy input from heavy bottoms plus increased energy input from natural gas and purchased hydrogen. As discussed in Section 6, these energy inputs are the sum of the allocated energy uses of the refinery units from which varies gasoline BOB streams are produced.

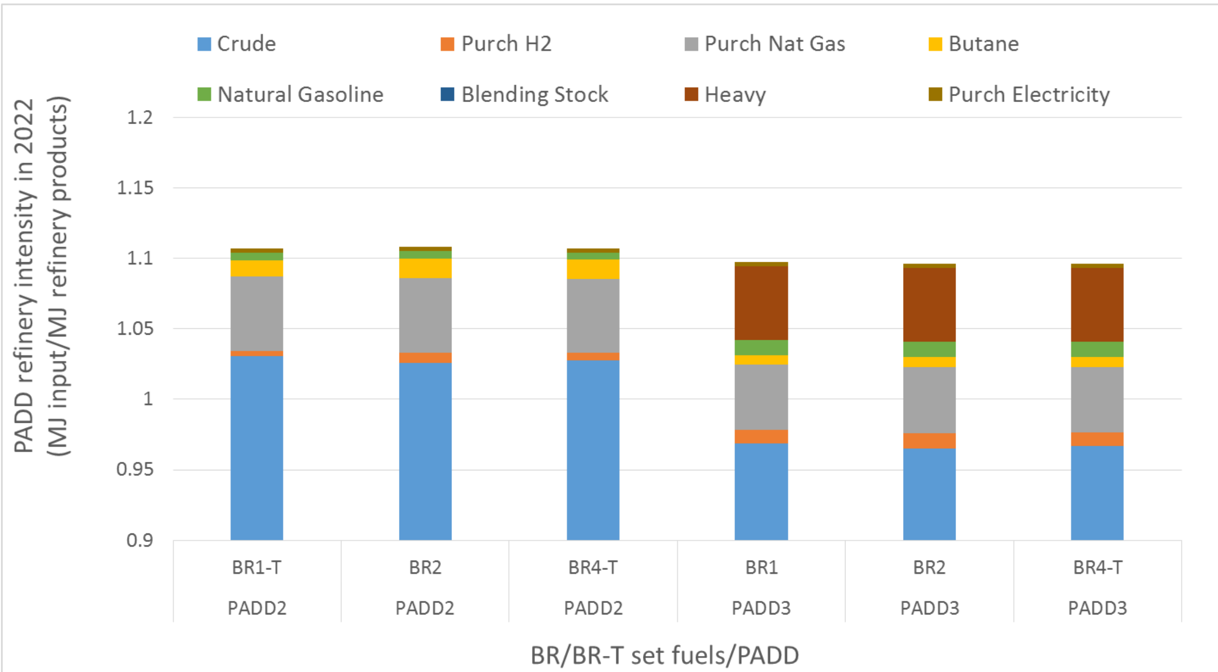


Figure 6-26. Refinery Energy Intensity with the BR/BR-T Fuel Production in PADD 2 and PADD 3 in 2022

In 2040, fewer LP modeling cases of the BR/BR-T set fuels productions were solved with feasible results (Figure 6-27). The energy input distribution in each PADD in 2040 is similar to that in 2022. Compared with the PADD 2 refinery with BR/BR-T fuels production, the PADD 3 refinery has less energy input from crude and butane but more energy input from heavy oil, natural gas, and purchased hydrogen. This is consistent with the trends observed for PADD base cases..

Overall refinery energy efficiency is shown in Figure 6-28.

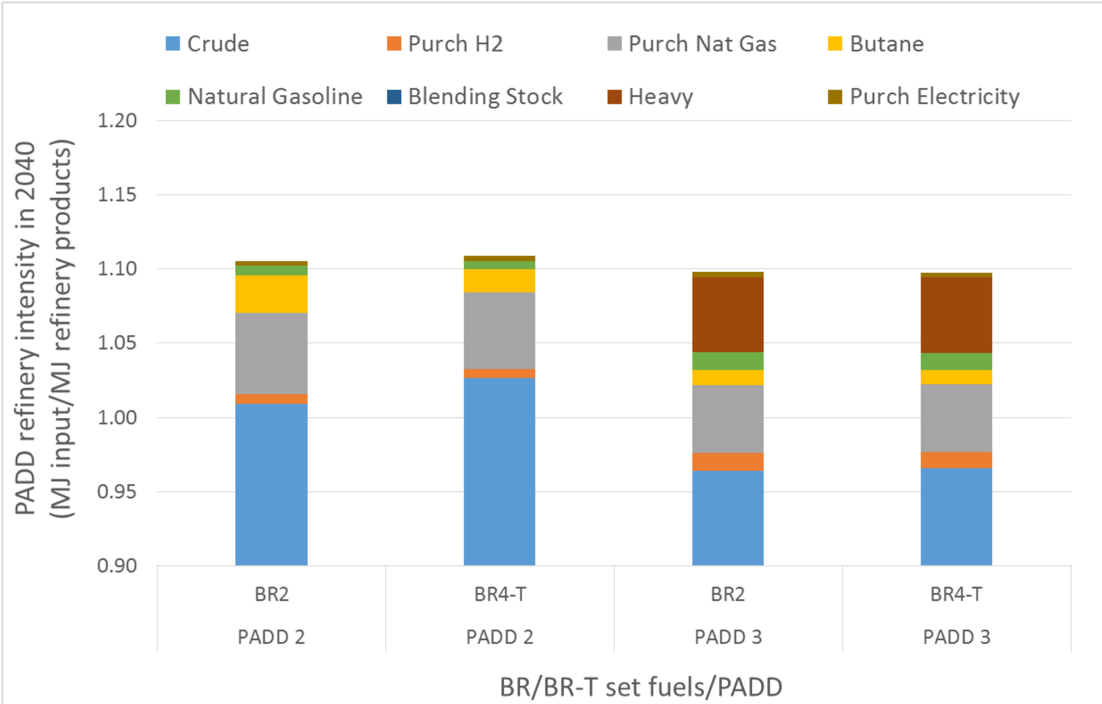


Figure 6-27. Refinery Energy Intensity with the BR/BR-T Fuel Production in PADD 2 and PADD 3 in 2040

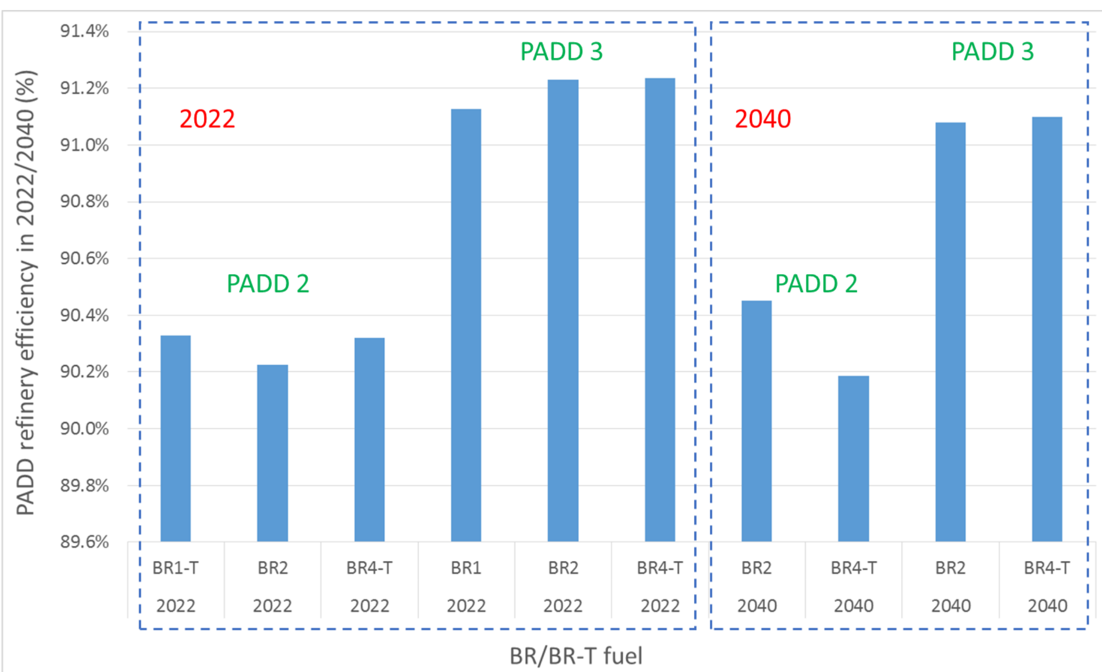


Figure 6-28. Overall PADD Refinery Energy Efficiency with the Production of BR Set Fuels in 2022 and 2040

For all three BR fuels, the PADD 3 refinery has higher energy efficiency than the PADD 2 refinery. The refinery efficiency difference among various BR set cases is rather small.

6.3.1.2 Gasoline Production Intensity and Efficiency of PADD Refineries with BR Set Fuel Production

In 2022, for each BR/BR-T set fuel produced in either PADD 2 or PADD 3, the energy intensity and energy input distribution for BAU, HOF and export gasolines differs (Figure 6-29). In 2022, the export gasoline intensity of BR set fuels is lower than that of baselines, so there is no burden shift to export gasolines. The gasoline produced in PADD 2 has more energy input from butane, while that produced in PADD 3 has more energy input from “heavy” (unfinished oil purchased from other refineries). For all gasoline production, natural gas provides a sizeable energy input in addition to the major input source of crude oil.

Similar observations were noticed for BR/BR-T gasoline production in 2040, shown in Figure 6-30. In 2040, the gasoline intensity in PADD 2, for both HOF and export gasoline, is higher than that in PADD 3, also different from that of the base cases with E10 production. The shifted export gasoline burdens were added back to HOF gasoline.

It is interesting to observe that for most BR or BR-T set gasolines, in both 2022 and 2040, BAU, HOF and export gasolines have different energy efficiencies, as shown in Figures 6-31 and 6-32. The differences are explained by their different stream components, which carry different energy burdens from the various refinery units in which they are produced.

Combining the BAU and HOF gasoline efficiencies (with weighted gasoline energy amounts) results in domestic gasoline efficiency, shown in Figure 6-33.

Each BR set domestic gasoline’s production efficiency is higher than that of the corresponding base case and varies with PADD and year. From 2022 to 2040, the energy efficiency of various BR set domestic gasolines increases.

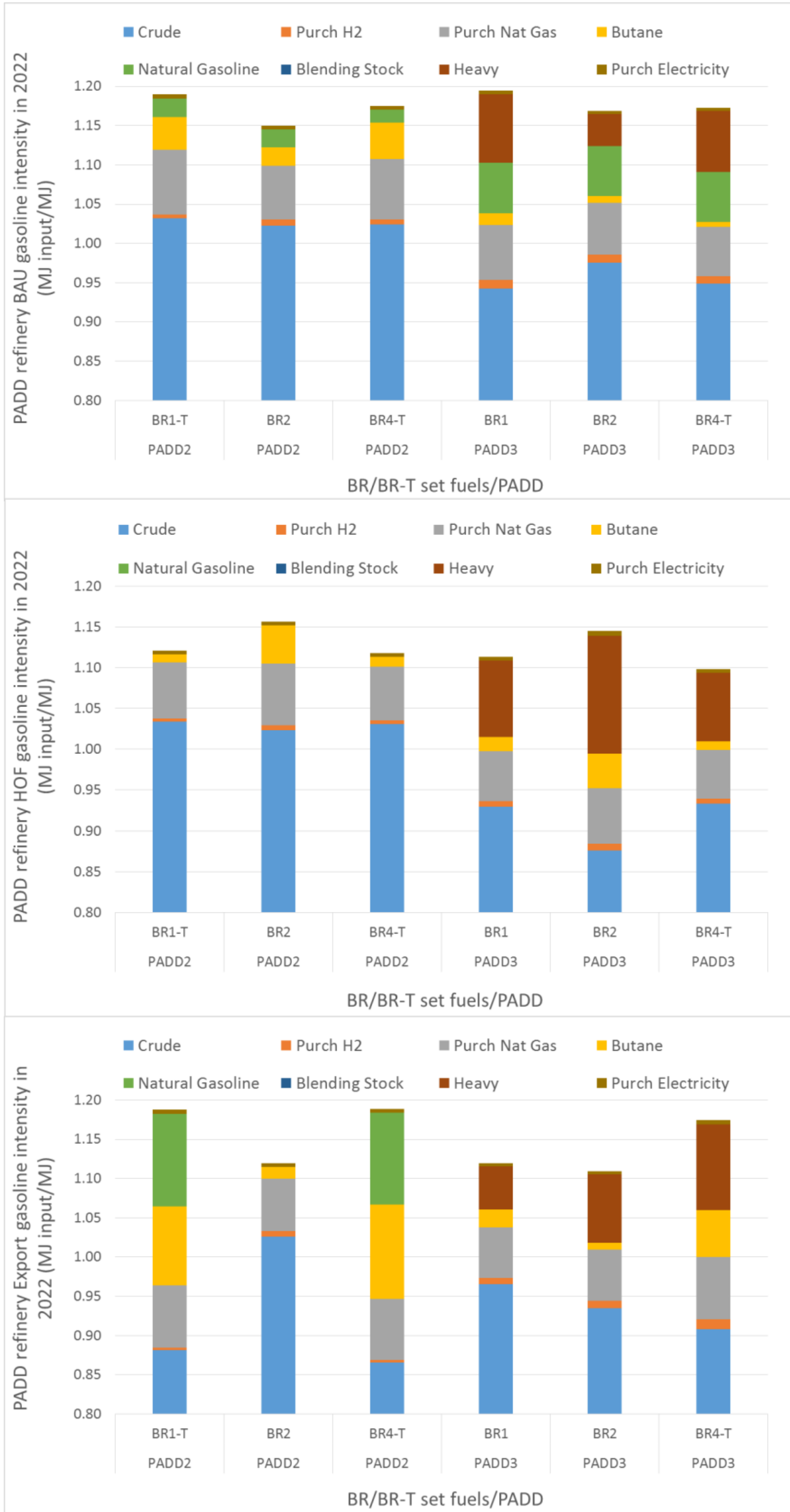


Figure 6-29. Refinery BR Set Gasoline Production Intensity in PADD 2 and PADD 3 in 2022

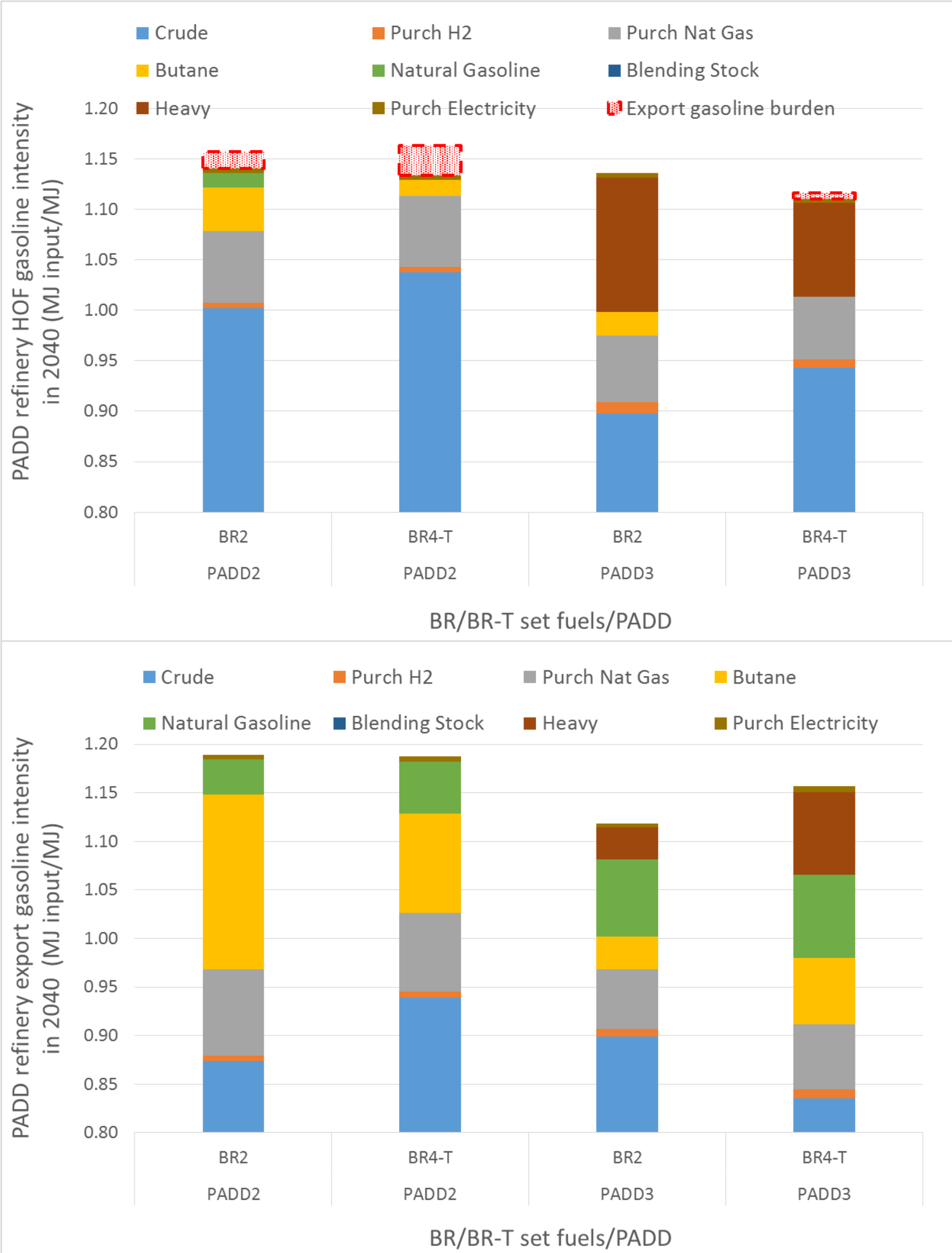


Figure 6-30. Refinery Gasoline Production Intensity in PADD 2 and PADD 3 in 2040

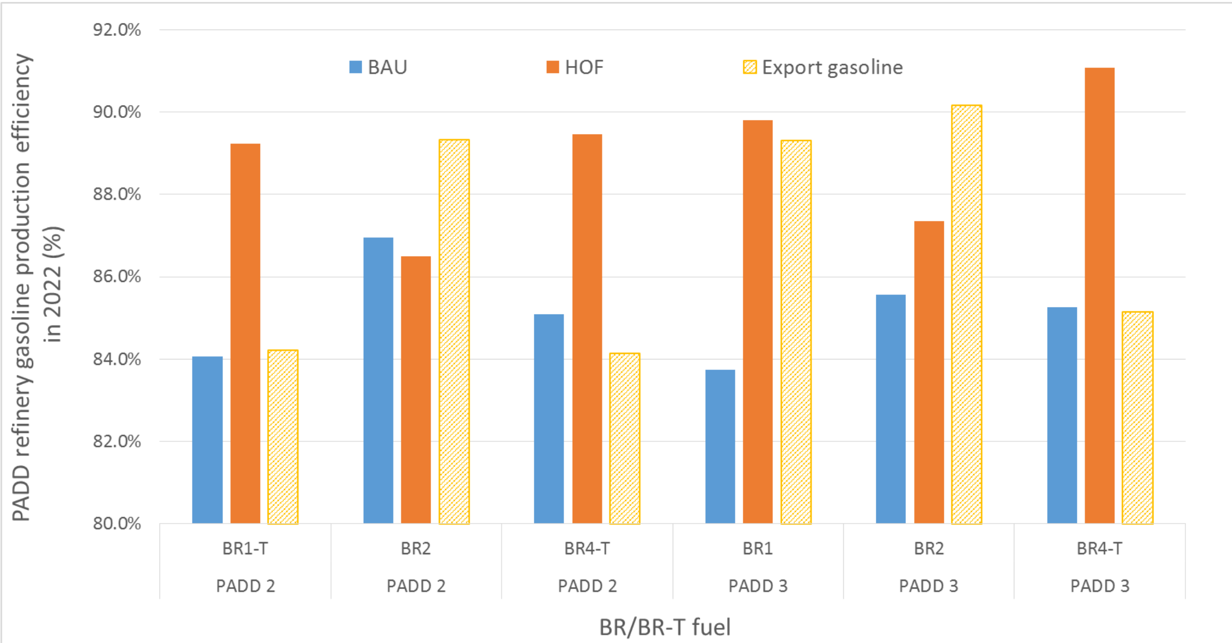


Figure 6-31. BR Set Fuel Gasoline Production Efficiency in PADD 2 and 3 Refineries in 2022 (BAU Gasoline, HOF Gasoline, and Exported Gasoline)

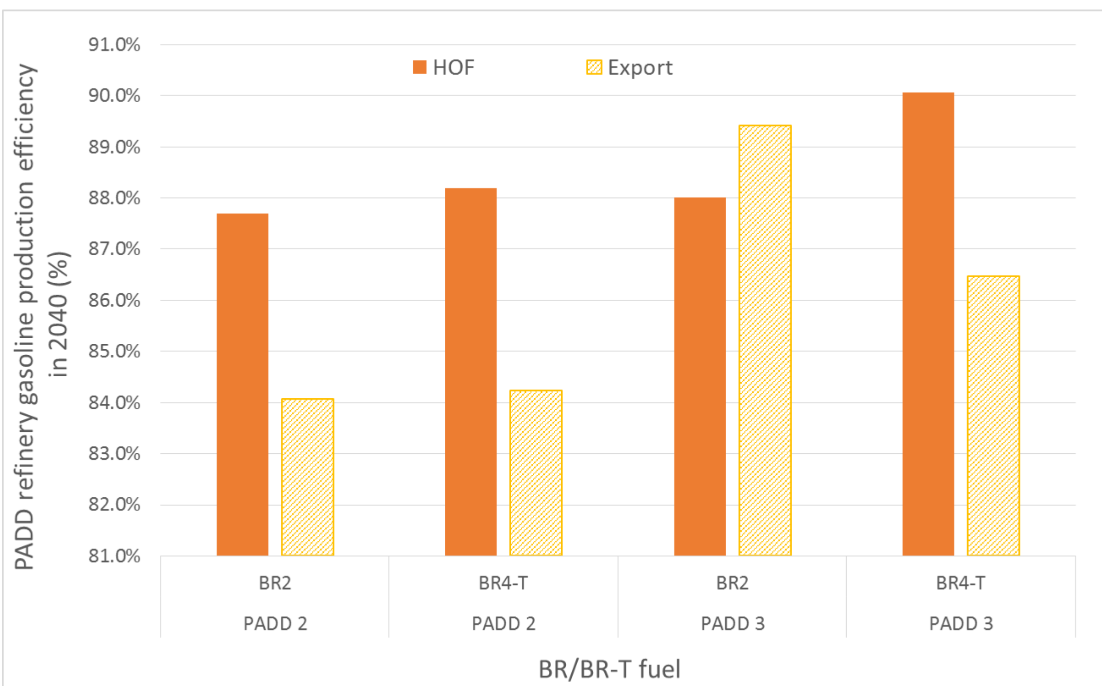


Figure 6-32. BR Set Fuel Gasoline Production Efficiency in PADD 2 and 3 Refineries in 2040 (HOF Gasoline andExport Gasoline)

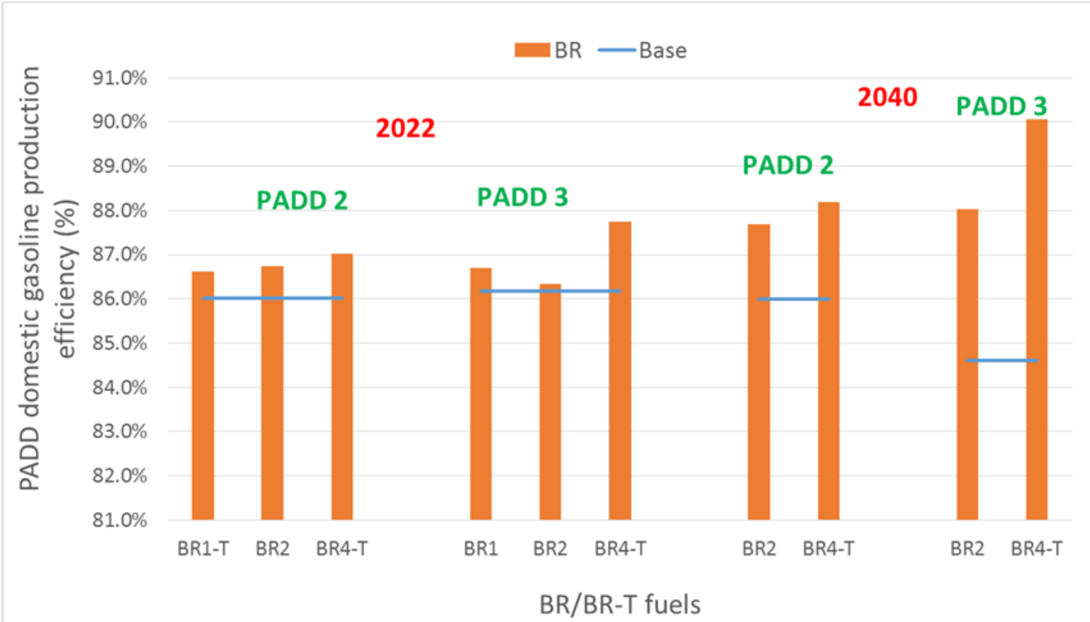


Figure 6-33. BR/BR-T Set Domestic Gasoline Production Efficiency in PADD 2 and 3 Refineries in 2022 and 2040

6.3.2 WTP GHG Emissions of BR Fuels Produced in Configuration Refineries

The modeling of BR set fuels production in configuration models was significantly challenged, with only the modeling of BR-2 production in 2022 having feasible solutions for CRK, LtCOK, and HvyCOK configurations. Using toluene as a surrogate resulted in feasible solutions for BR4-T. No COKHCK refinery modeling yielded feasible solutions. The results are discussed below.

6.3.2.1 Overall Energy Intensity and Efficiency of Configuration Refineries with BR Set Fuels Production

For 2022 and 2040, the overall configuration refinery energy intensities for producing the BR/BR-T fuels with feasible solutions are shown in Figure 6-34.

As expected, for each BR or BR-T set fuel, the overall refinery intensity increases with increasing configuration complexity. The energy inputs are mainly from crude oil, natural gas, butanes and electricity. With increasing refinery complexity, the natural gas energy input increases sharply.

The overall refinery efficiencies of these configuration refineries with BR fuels production in 2022 and 2040 are shown in Figure 6-35.

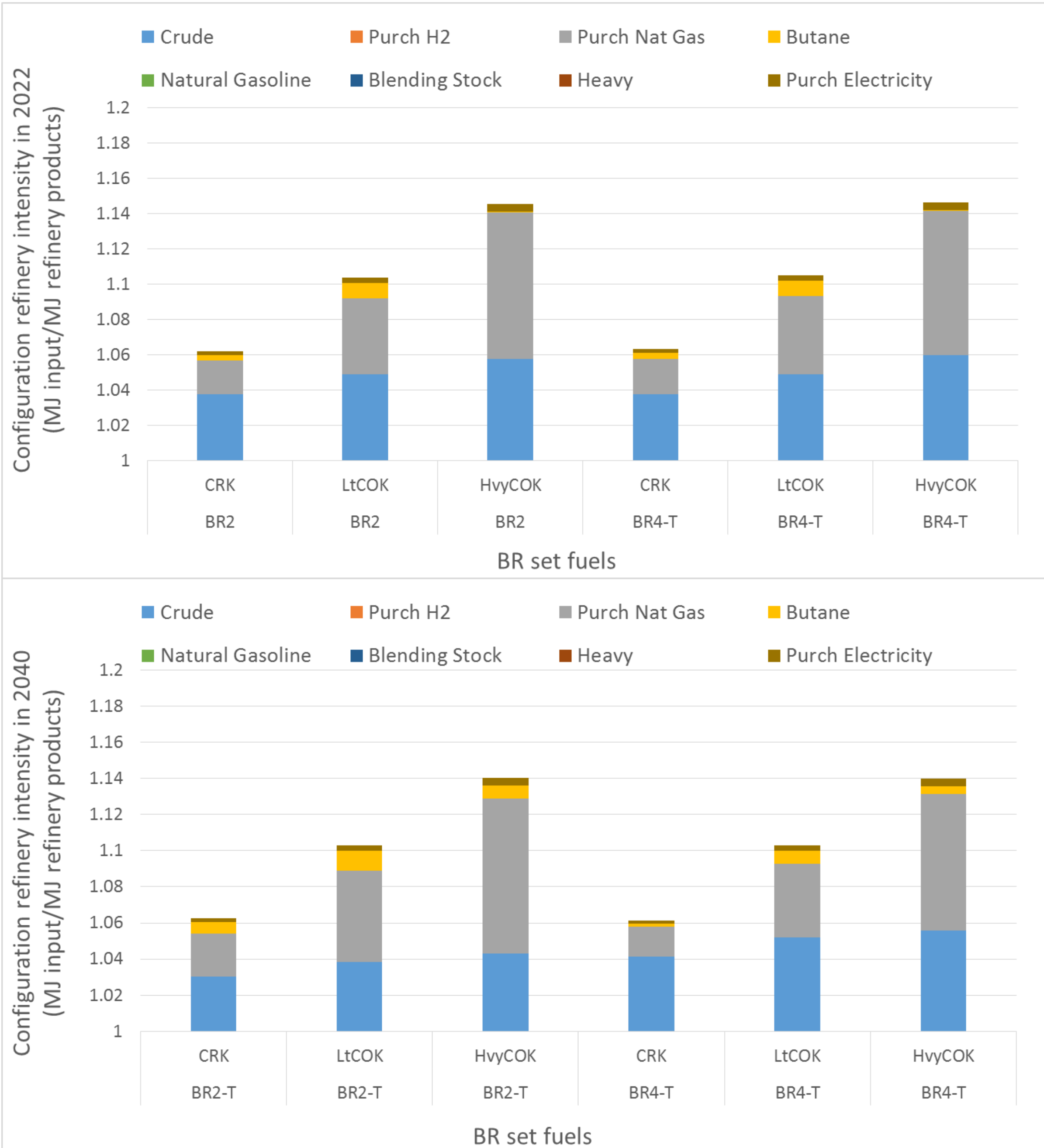


Figure 6-34. Configuration Refinery Energy Intensity (with BR/BR-T set fuel production) in 2022 and 2040

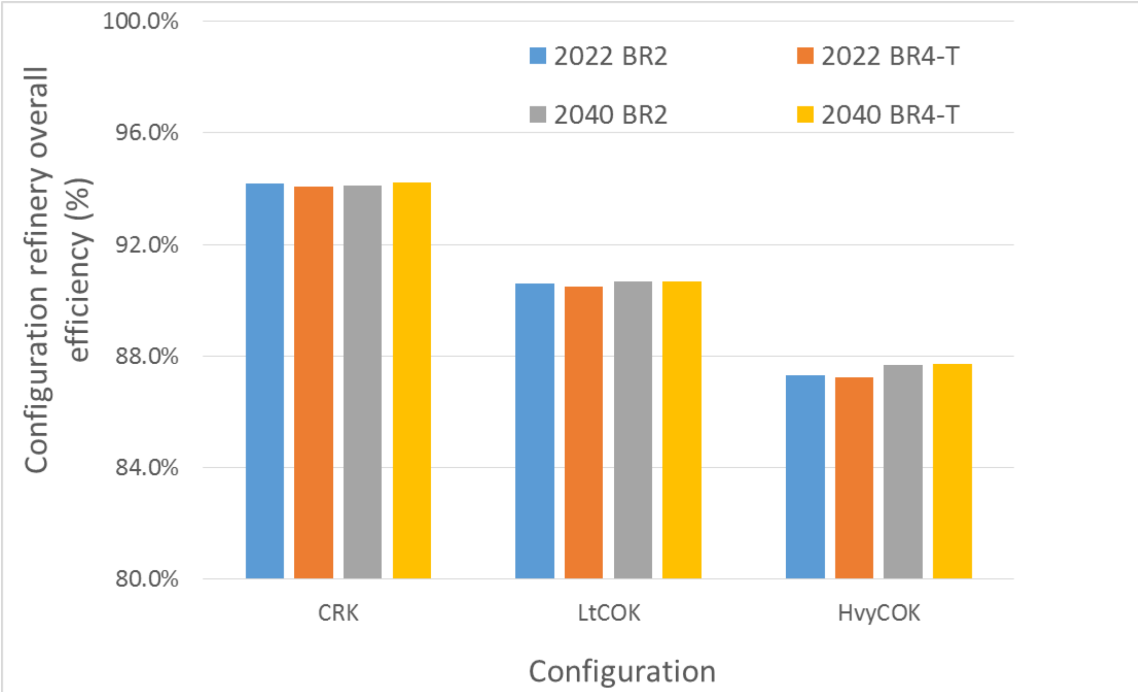


Figure 6-35. Overall Efficiency of Various Configuration Refineries with BR Set Gasoline Production

For all the BR set fuels, the overall efficiency of the configuration refinery decreased with increasing complexity. On the other hand, for a given configuration the overall refinery efficiencies for BR2 and BR4-T are similar, as are the efficiencies in 2022 and 2040.

6.3.2.2 Energy Intensity and Efficiency for BR Domestic Gasoline BOB Production in Configuration Refinery

In 2022, the BR domestic gasoline volume is equally split between BAU and HOF gasoline (although these are not equal in energy share due to HOF having higher energy content), and the export amount is minimal (about 0.01%–0.7%). The gasoline intensity for BAU, HOF and export gasoline are shown in Figure 6-36.

Most of the HOF gasolines of BR/BR-T set fuels have higher energy intensities than their BAU gasoline counterparts, mainly because of the increased input from natural gas and butanes. It is worth noting that HOF gasoline has a much larger C4s component than BAU gasoline (5–6 vol% vs 1–2 vol%), as shown in refinery analysis. This suggests that butane is used for blending rather than for alkylation feed. This butane amount in HOF is also much higher than that in the E set gasoline (both BAU and HOF gasoline), suggesting that the heavy BR or BR-T stream allows more blending of light butanes/C4s to balance distillation properties.

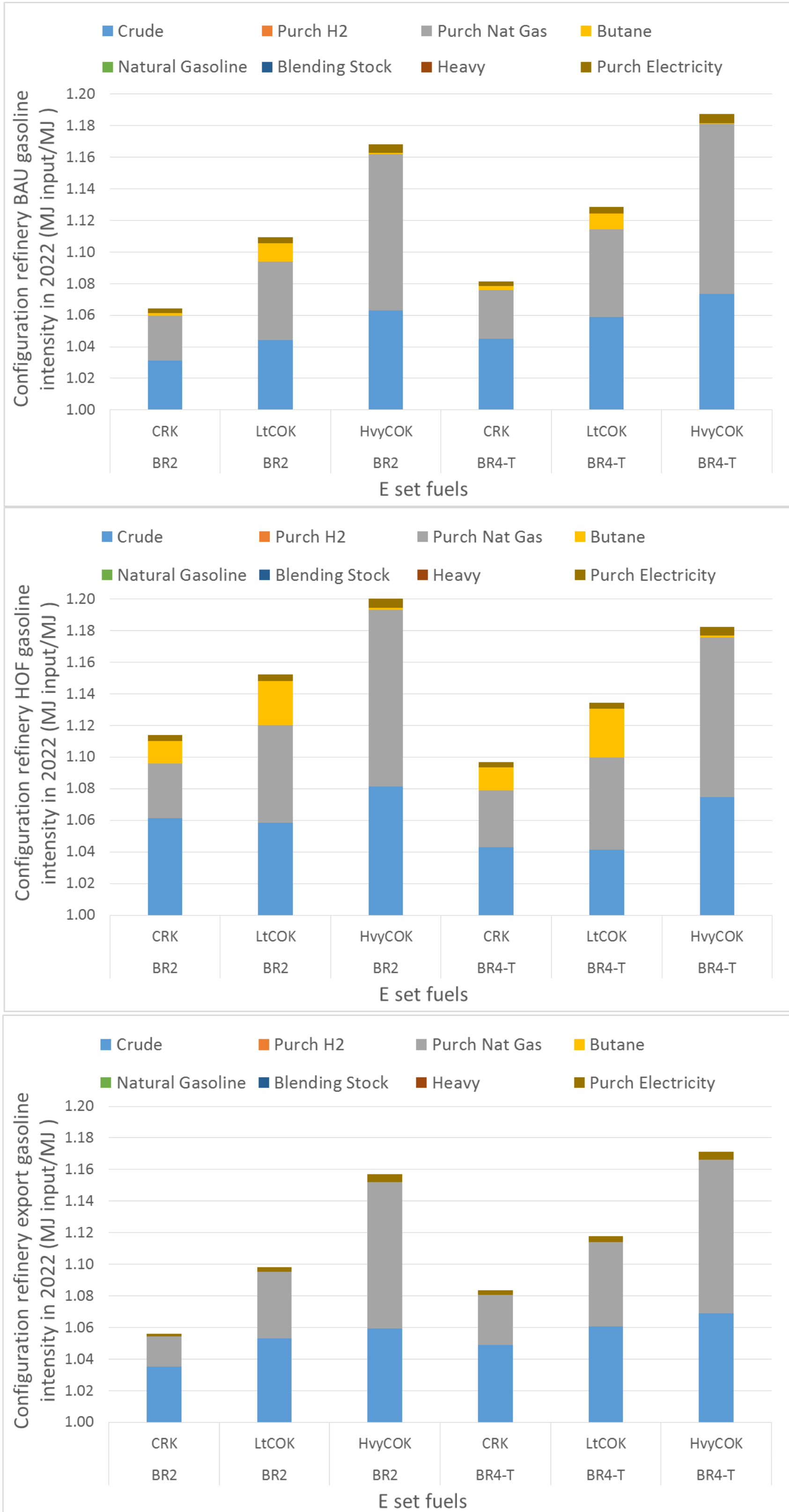


Figure 6-36. BR/BR-T Set Gasoline Energy Intensity in Configuration Refineries in 2022

The BR/BR-T set gasoline energy intensities in 2040 are also shown in Figure 6-37. In 2040, all domestic gasolines are HOF; however, export gasoline increases to 11–17 vol% (except for BR2-T in a CRK refinery, with 0.1% export). Although the export gasoline volume increases for all BR set cases, the burden shift is negligible as their intensities are only slightly higher than or similar to those of baselines. Both HOF and export gasoline intensities are shown in Figure 6-37.

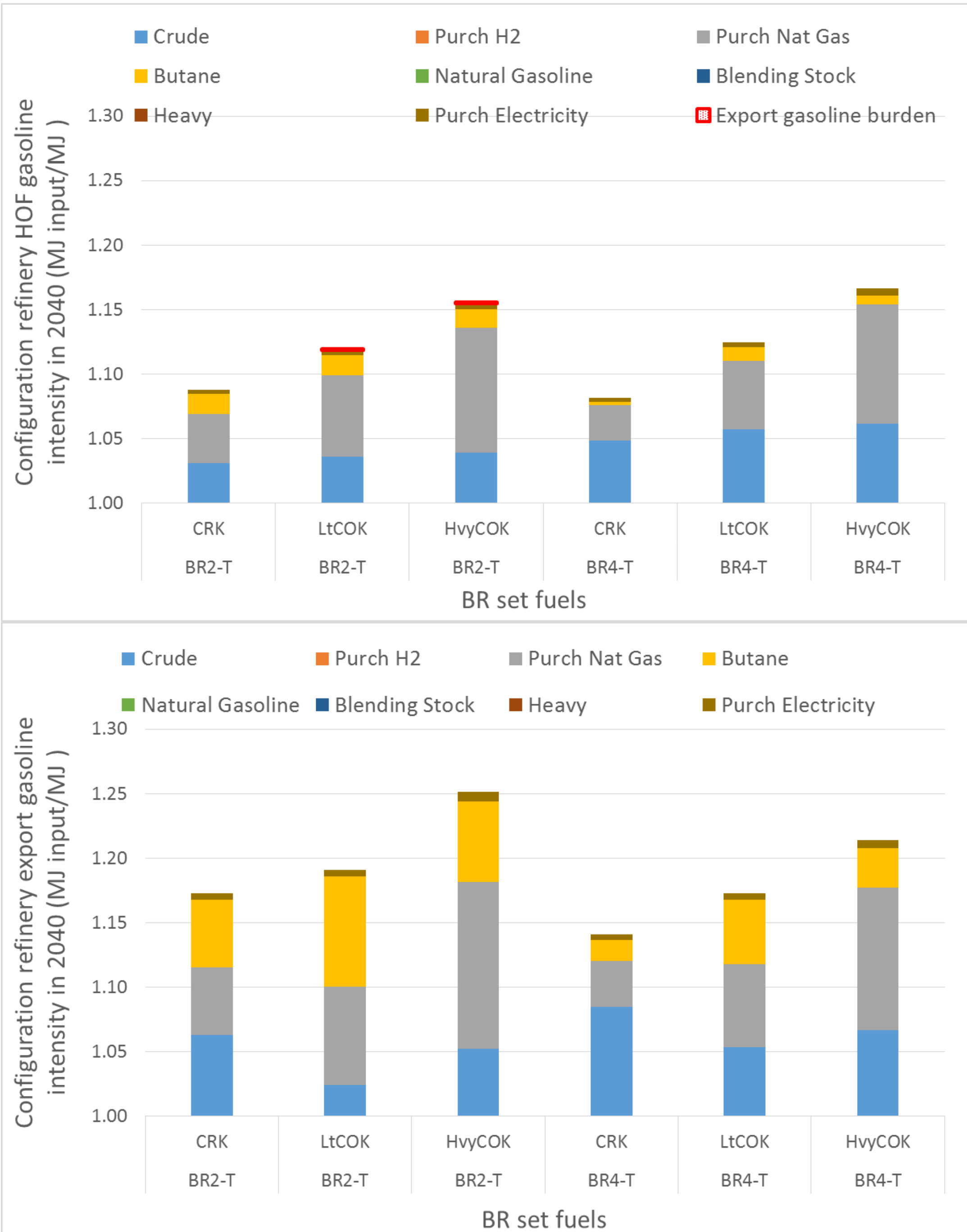


Figure 6-37. BR/BR-T Set Gasoline Energy Intensity in Configuration Refineries in 2040

The gasoline energy intensities in 2040 show high butane share in all energy input, especially for export gasoline. However, in HOF gasoline, butane is mostly used for blending, as evidenced by the 5vol% of C4s component in HOF pool (see Section 5). For export gasoline, the butane input is used for alkylation, as the export gasoline has 0% C4s component and high shares of alkylate blending component (31–62 vol%) (see Section 5).

The BR gasoline production efficiency in each configuration refinery in 2022 is shown in Figure 6-38. Both BAU and HOF gasoline efficiencies are presented.

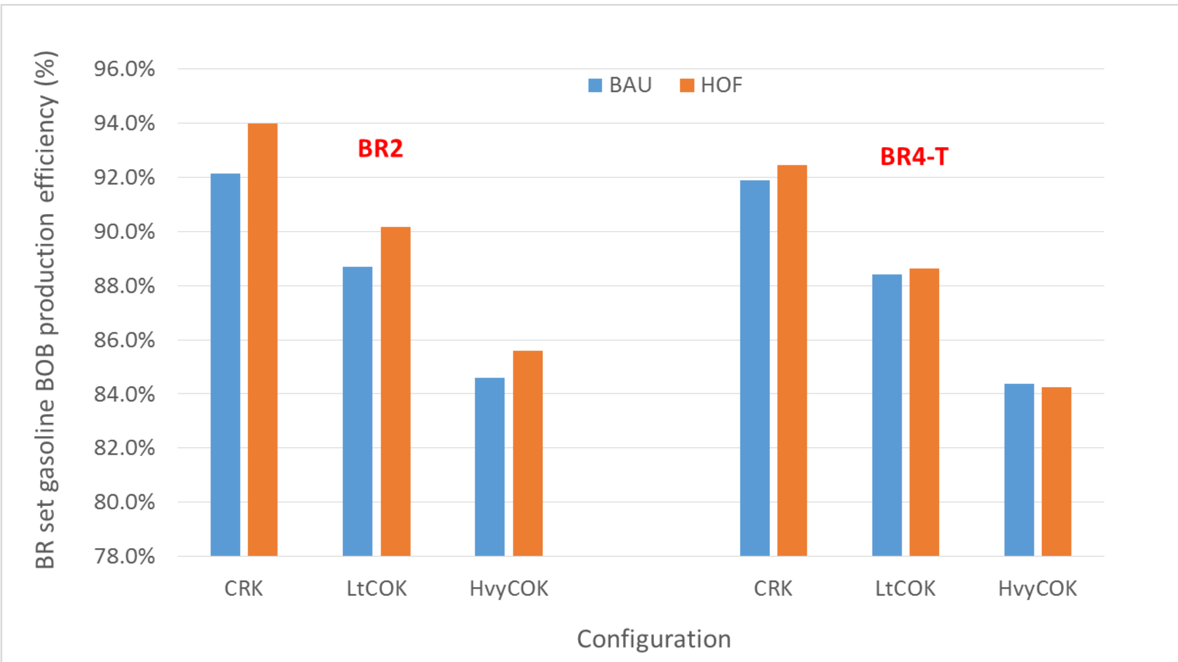


Figure 6-38. BR Set Gasoline Efficiency (BAU and HOF) in Configuration Refineries in 2022

For BR2 set fuels, in each configuration, the BAU gasoline has a lower efficiency than HOF gasoline. In contrast, for BR4-T the efficiency difference between BAU and HOF gasolines is smaller. As stated previously, this is explained by the different gasoline component shares and the corresponding refinery unit's energy use. With increasing refinery complexity, the gasoline efficiency decreases (see Figure 6-39).

For the CRK configuration, the gasoline efficiency of the different fuels in different years is quite similar. For the more complex LtCOK and HvyCOK configurations, the efficiencies in 2040 are higher than in 2022 due to the lower input of natural gas, butane, and crude in 2040. These input changes could be driven by a product slate change, such as the G/D ratio. The more complex refinery (e.g., HvyCOK), has a large natural gas input, and is therefore sensitive to natural gas input change.

Figure 6-40 shows different gasoline efficiencies for export gasoline.

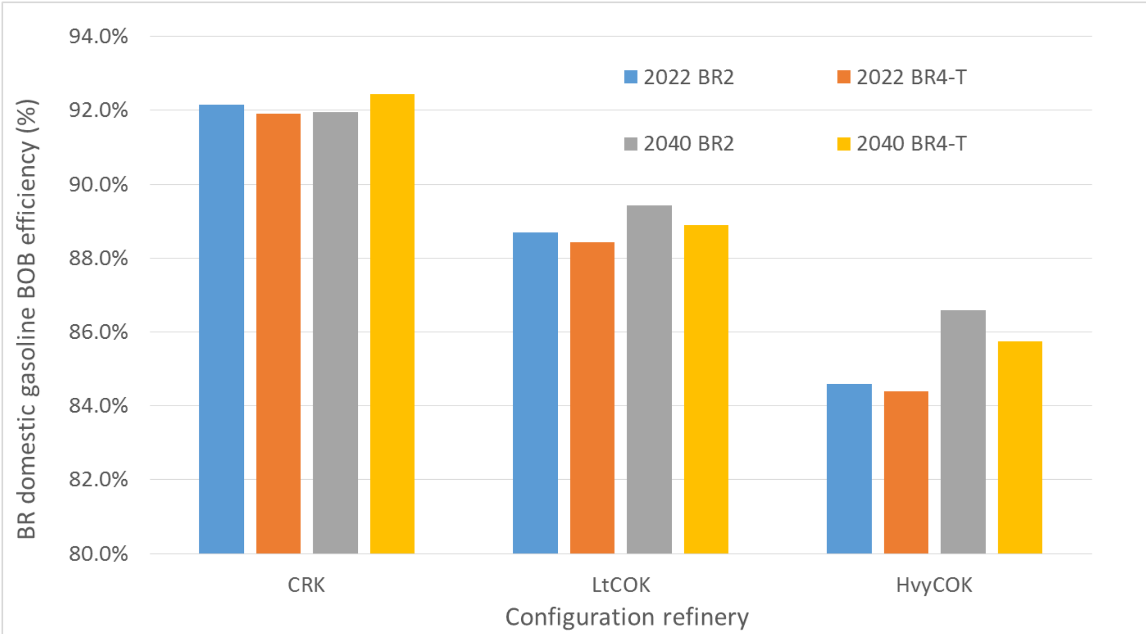


Figure 6-39. BR Domestic Gasoline BOB Efficiency at Configuration Refineries in 2022 and 2040

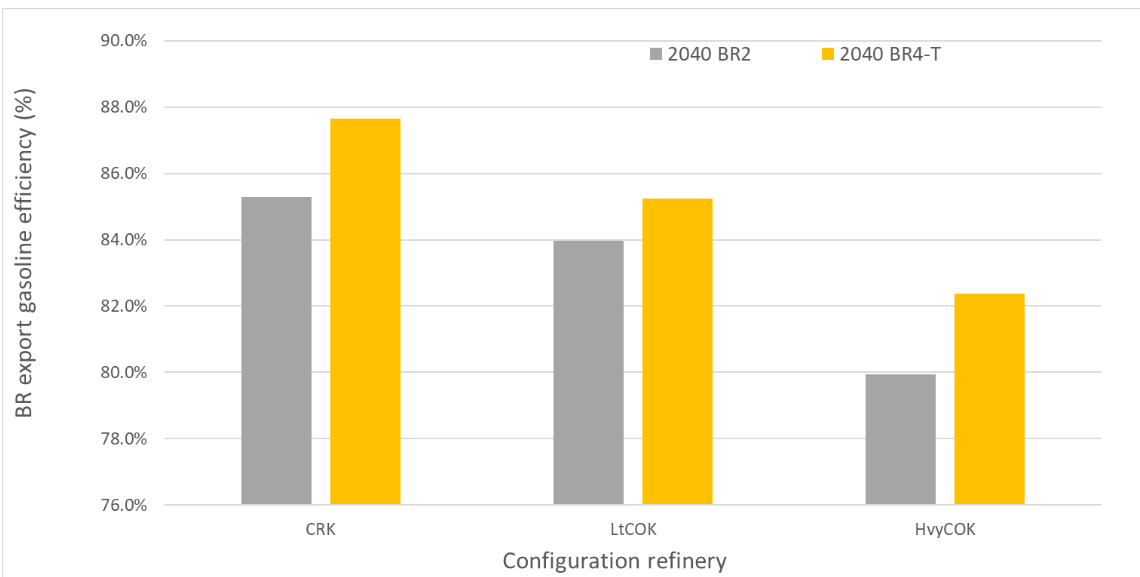


Figure 6-40. BR Set Exported Gasoline Energy Efficiency in Configuration Refineries

The export gasoline efficiency in 2022 is not shown, as the export amount is minimal. In 2040, for both BR2 and BR4-T, the export gasoline efficiency is lower than that of domestic gasoline (export gasoline does not contain any ethanol). This is consistent with the higher energy intensity of export gasoline, mostly attributed to the higher energy input from butane use.

7. WTP Energy Uses and GHG Emissions of Gasoline BOBs, Ethanol, and BR

This section summarizes the WTP energy use and GHG emissions for gasoline BOBs, bio-ethanol and bioreformate, respectively. The WTP GHG emissions of gasoline BOBs are estimated by combining the GHG emissions from feedstock stage (crude recovery and crude transportation) and from fuel production stage (the refining process, with results derived from LP modeling results). The WTP calculation of GHG emissions of the two bio-blendstocks (ethanol and bioreformate) were already developed in GREET 2016. Thus, the default values of GREET 2016 were used for WTP GHG emissions for the biofuel feedstock stage (agriculture and transportation) and the biofuel production stage (biomass conversion to biofuel and transportation).

In this section, the WTP analyses of gasoline BOBs are discussed in details in order to show how the changes in refinery operations driven by HOF fuels production, governed by LP modeling, are translated to the variations in WTP energy uses and GHG emissions for gasoline BOBs production. The WTP results for the finished fuels are calculated by combining the results of gasoline BOBs and that of ethanol or bioreformate based on their energy content shares, and are presented in Appendix 3.

It is worth emphasizing that as the WTP results of finished gasolines depend on the results of gasoline BOB, bio-blendstock and their energy shares, higher energy use or GHG emissions per MJ of BOB does not necessarily imply higher energy use or GHG emissions per MJ of finished fuel after blending bio-ethanol or bioreformate.

7.1 WTP Results for E Set Gasoline BOBs

The WTP energy use and GHG emissions of E set fuels BOBs are discussed below.

7.1.1 WTP Analysis of Aggregate Refineries Base Case Gasoline BOBs

The base case scenario is continuous adoption of incumbent regulations and specifications and the continuous, business-as-usual production of E10 in 2022 and 2040. The crude slate, product slate, and/or electricity mix will change over time based on the EIA projection. Refinery energy use and WTP GHG emissions of base case gasoline BOB production are summarized below.

WTP energy use for producing gasoline BOBs is shown in Figure 7-1.

Figure 7-1 shows that the energy use for gasoline BOB production is mostly fossil energy, and petroleum energy use is 20–30% of the total. Because direct and indirect (for electricity generation) coal use is much smaller during the WTP stage (crude recovery, refining process, and transportation, as shown in the GREET WTP results of ethanol production model), the difference between fossil energy and petroleum energy is mostly attributable to natural gas use.

PADD 2 refineries consume much larger amounts of fossil energy, mostly natural gas at the feed stage (crude recovery), attributable to the recovery of energy-intensive Canadian oil sands. In the fuel stage (refining process), PADD 3 and CA refineries use more fossil energy (mostly natural gas) than PADD 2 refineries do because of the greater hydrogen demand in PADD 3 and CA.

The GHG emissions of base case gasolines for different regions and different years were analyzed to serve as baselines for comparison with high-octane bio-blended fuels. They are shown in Figure 7-2.

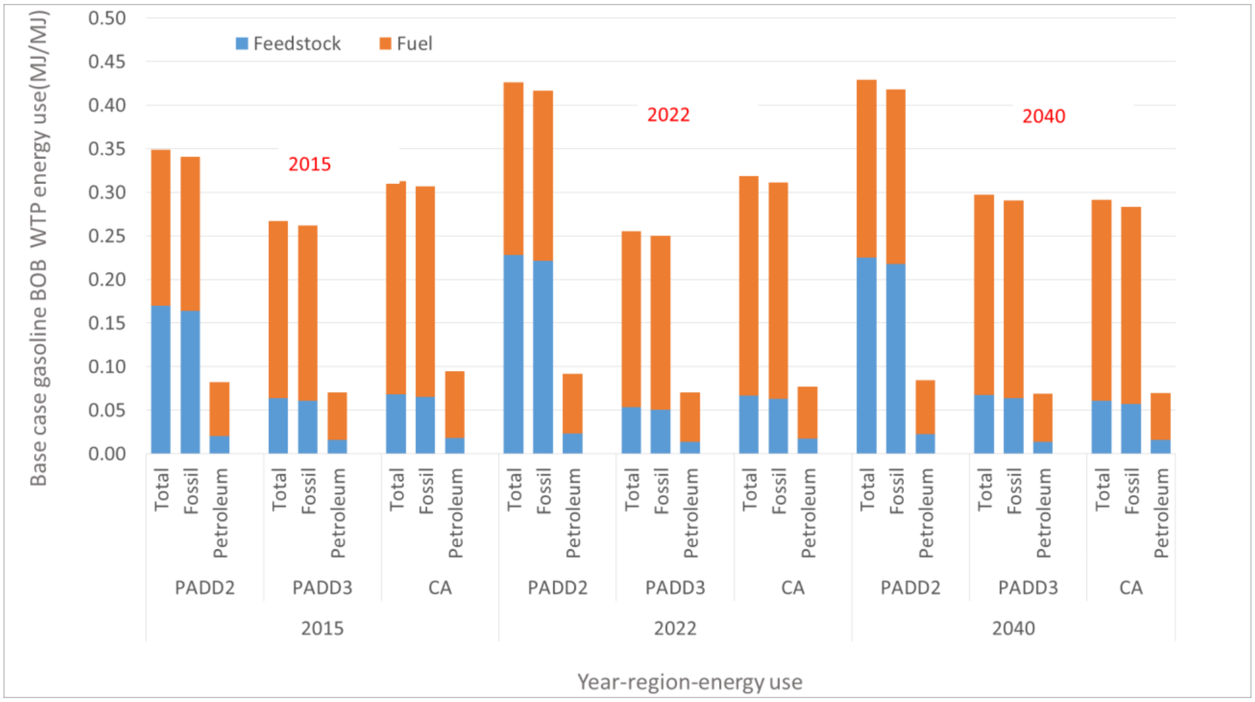


Figure 7-1. WTP Energy Use of Gasoline BOB Production for Aggregate Base Case Domestic Gasoline Pools

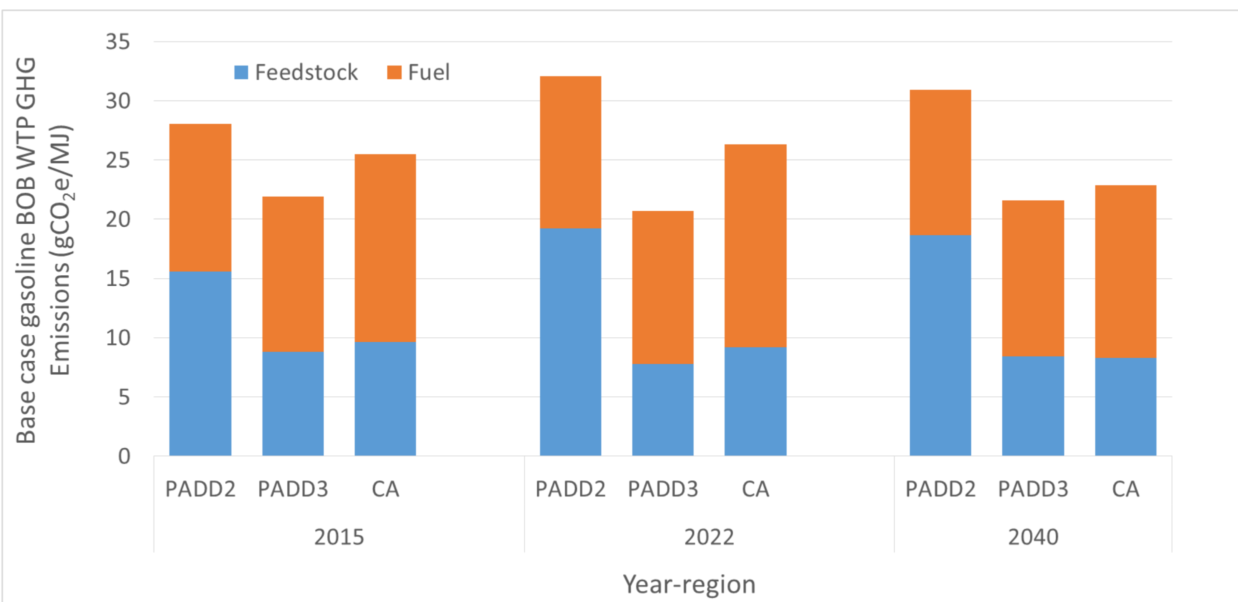


Figure 7-2. WTP GHG Emissions of Gasoline BOB Production for Base Cases (g/MJ)

In Figure 7-2, the BOB “feedstock” stage refers to crude recovery and transportation, and BOB “Fuel” refers to refinery process and gasoline BOB transportation and distribution. The BOB fuel stage not only includes on-site emissions (from both combustion and non-combustion sources), but also includes the upstream emissions of material/energy supply to refineries, such as natural gas and electricity. For all the studied years, the base cases in PADD 2 have significantly higher GHG emissions in the crude recovery and transportation stage (BOB feedstock) than PADD 3 and CA. This is because PADD 2 refineries process more Canadian oil sands, which are more GHG emission intensive than conventional crudes and shale crudes. In contrast, for all years, in the BOB fuel stage (refinery process and transportation/distribution), the base cases in CA have higher GHG emissions than those in PADD 2 and PADD 3. This is attributed to their higher natural gas use, driven by CA refineries’ higher hydrogen demand, for producing fuels meeting CA specifications with significant heavy crude inputs.

7.1.2 WTP Analysis of Aggregate Refineries E Set Gasoline BOBs

As shown in Section 5, for 2022, LP modeling for all E set fuels in PADD 3 was solved (feasible), and the domestic gasoline pool consists of 50 vol% BAU gasoline and 50 vol% HOF gasoline. The different octane requirements of the two gasoline pools lead to different pool compositions, which inherit and carry different burdens sourced from refinery unit processes and corresponding upstream energy input (crude, natural gas, electricity, etc.). All the differences in these elements contribute to different energy use and GHG emissions for the BAU and HOF gasoline BOB for each E set fuel, the energy uses are shown in Figure 7-3 below.

Figure 7-3 shows that BAU and HOF gasoline BOB have similar energy use during the feedstock stage (energy input, e.g., crude recovery allocated to gasoline production), but different energy use in the fuel production stage. This is consistent with their different fuel components and different energy intensity/efficiency, shown in Sections 5 and 6, respectively. For the HOF gasoline BOBs, the production of the BOB for F16, the 101 RON E10 fuel, requires less total energy use and less fossil energy use than production of the BOB for F18, the 101 RON E20 fuel.

Combining the energy use of BAU gasoline BOB and HOF gasoline BOB results in the energy use of domestic gasoline BOB in PADD 3 in 2022. A comparison of E set domestic gasoline BOBs with baseline is shown in Figure 7-4.

Most E set domestic gasoline production uses the similar amount of energy as baseline gasoline production, or less. It is worth noting that F16 BOB uses more petroleum energy than baseline, which is consistent with the slightly higher crude input for F16 production, discussed in Section 6. Meanwhile, F16 BOB production use less total energy and less fossil energy than the BOBs for the other HOFs with higher ethanol levels (F18 and F19).

As expected, a similar energy use during the feed stage results in similar GHG emissions for all E set gasoline BOBs. The slight energy use difference at the fuel production stage (refining process burden allocated to gasoline pool) shown in Figure 7-5 below translates to small variations in GHG emissions of about 1 g CO_2e/MJ or less.

Several fuels (F7, F14, F16, and F18) BOB show higher GHG emission than the baseline in response to the high octane requirement of the HOF gasoline pool. The opposite trend is observed for Fuel 15 BOB. This F15 finished gasoline blends 30% ethanol and has a mid-level octane demand, which provides significant octane to the gasoline pool and eases the refinery’s challenge to produce high-octane BOBs, usually via energy-intensive unit processes

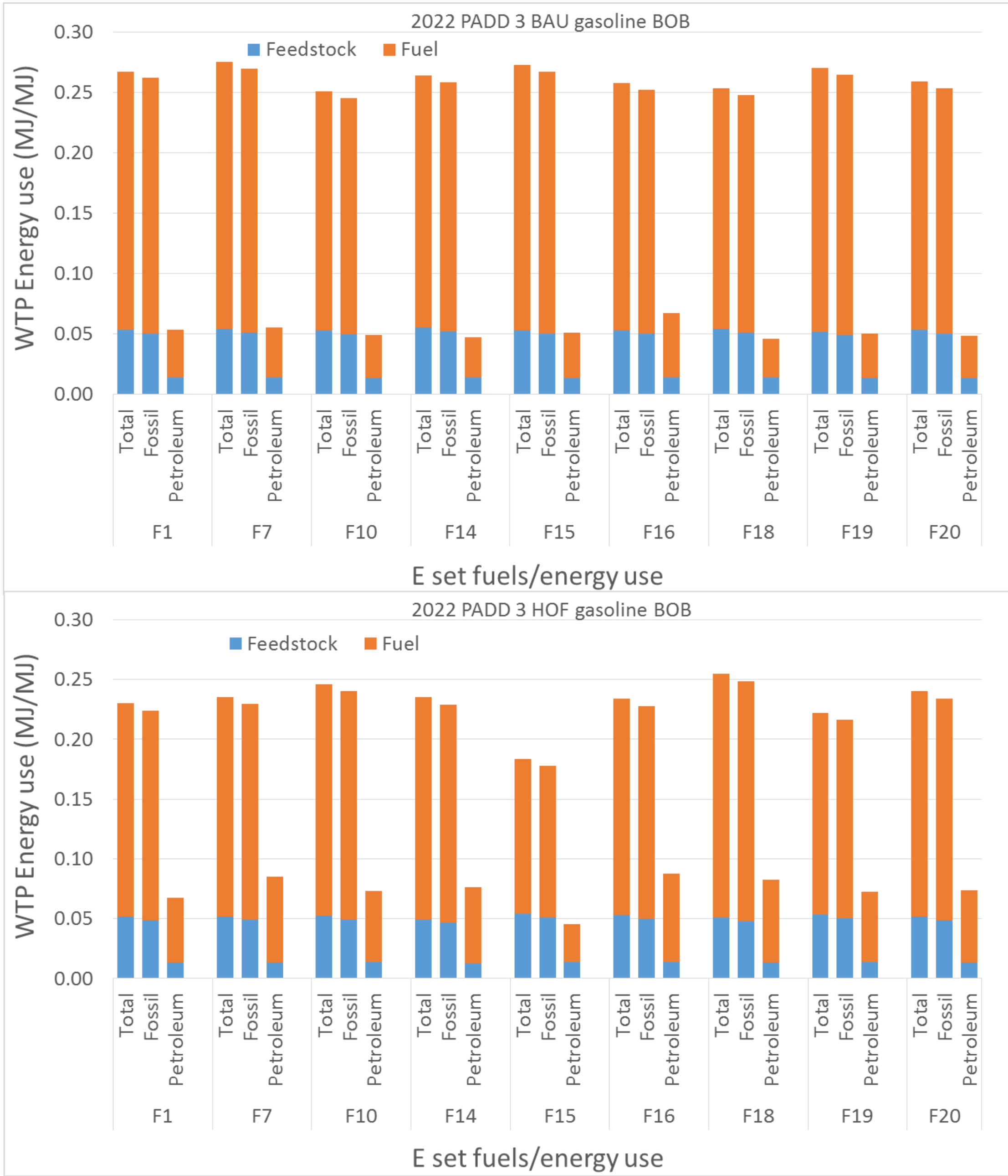


Figure 7-3. WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of E Set Gasoline BAU BOB and HOF BOB in PADD 3 Refinery in 2022

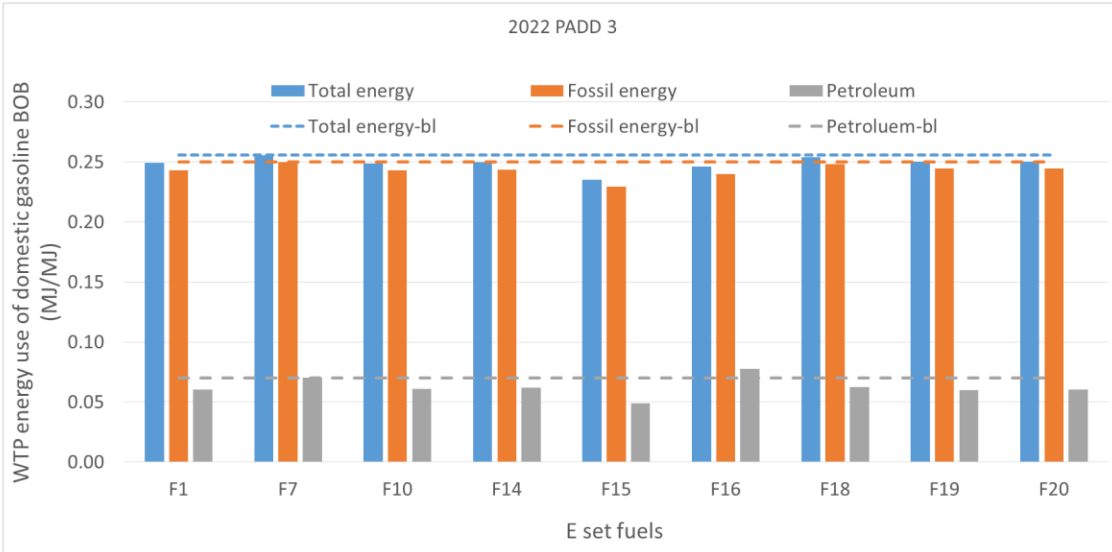


Figure 7-4. Comparison of WTP Energy Use for the Production of E Set Domestic Gasoline BOBs with Baseline in PADD 3 Refinery in 2022

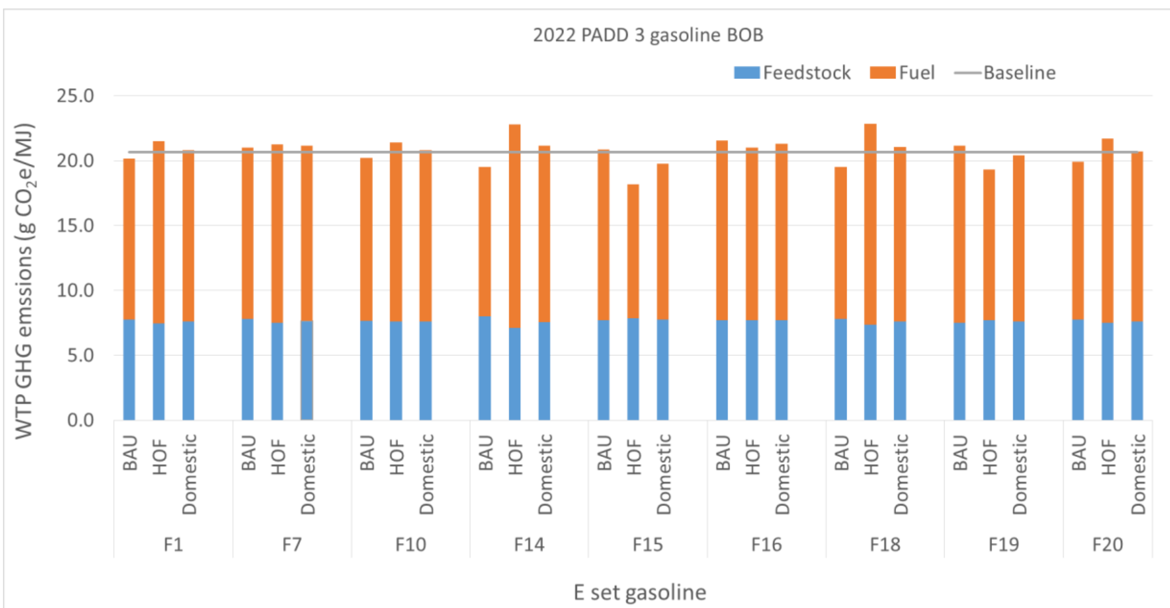


Figure 7-5. GHG Emissions of BAU and HOF Gasoline BOB Production in PADD 3 in 2022

WTP energy use and GHG emissions of E set gasoline BOBs in CA in 2022 are shown in Figure 7-6, 7-7 and 7-8.

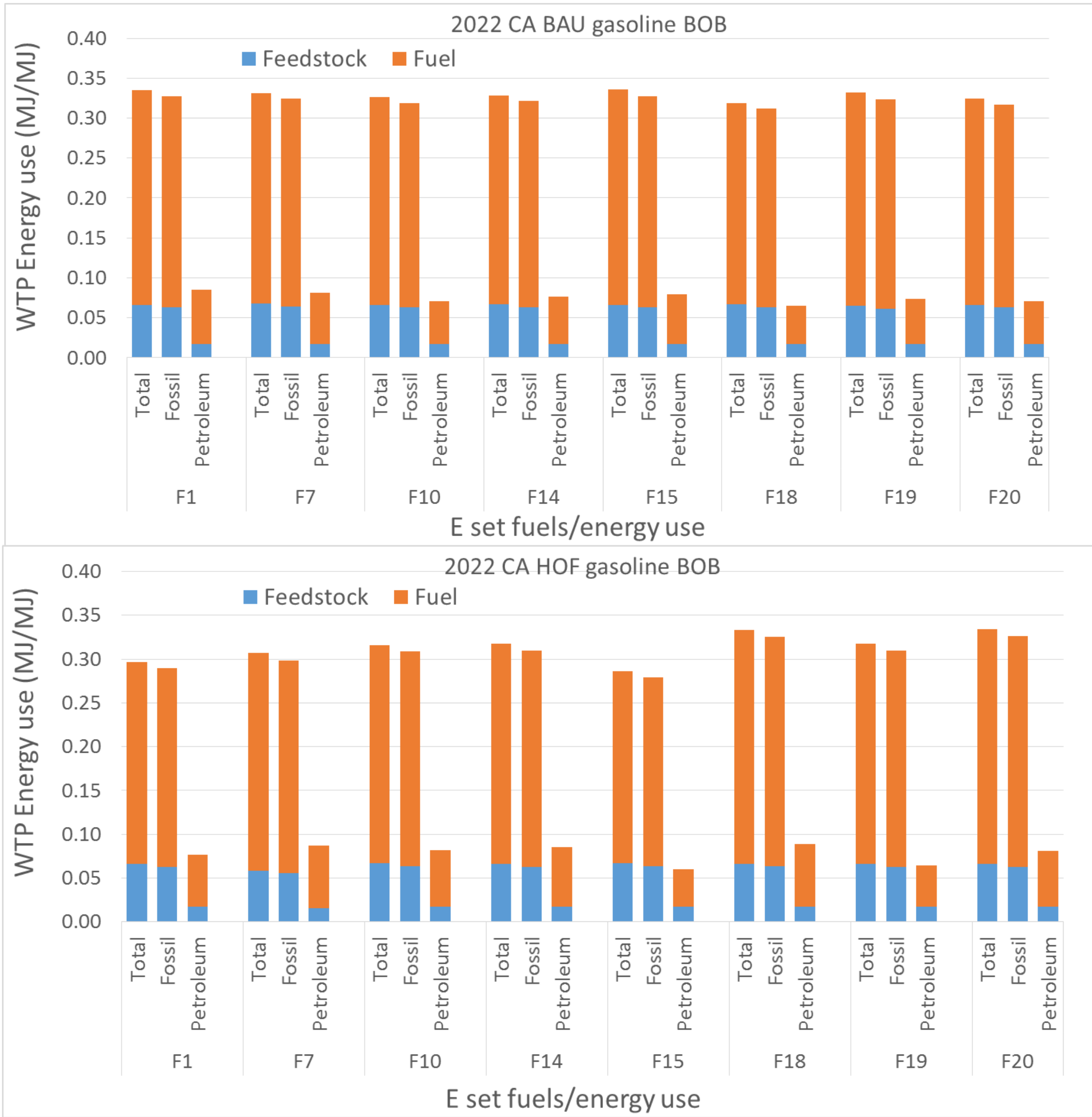


Figure 7-6. WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of E Set Gasoline BAU BOB and HOF BOB in CA Refinery in 2022

A comparison of BAU gasoline energy use to HOF gasoline energy use is not the same for each E set fuel. This is related to the different component shares in each gasoline pool, which in turn result from overall refinery optimization to seek maximum profits while meeting high octane demand. The energy use differences among E set BAU gasolines are rather small, while the energy differences among HOF gasolines are more pronounced, owing to their different properties that meet different octane demands.

As expected, the energy use for domestic gasoline production in CA is larger than in PADD 3. As in PADD 3, Fuel 7, F14, and F18 show slightly higher energy use than baseline (see Figure 7-7.). This is mostly due to the use of more natural gas and butane than in the base cases.

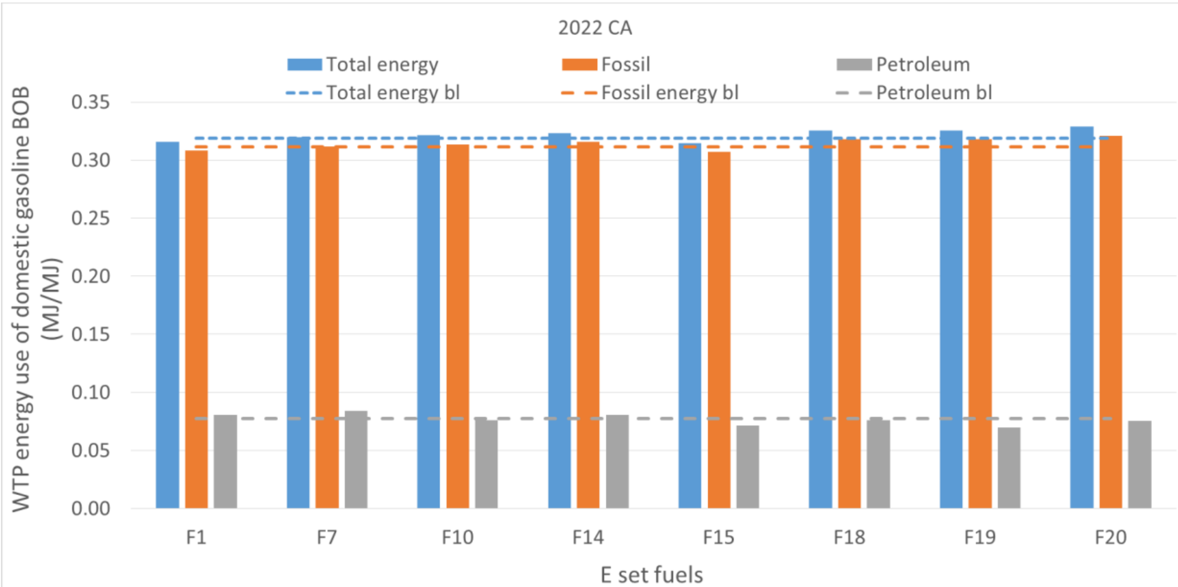


Figure 7-7. Comparison of WTP Energy Use for the Production of E Set Domestic Gasoline Pool BOBs with that of Baseline in CA Refinery in 2022

GHG emissions of E set gasoline BOB production in a CA refinery in 2022 are shown in Figure 7-8 below.

A comparison of BAU production GHG emission to HOF production GHG emissions is different for each E set fuel, and either can be higher or lower than baseline GHG emissions. However, the difference between the combined domestic gasoline and the baseline is less pronounced.

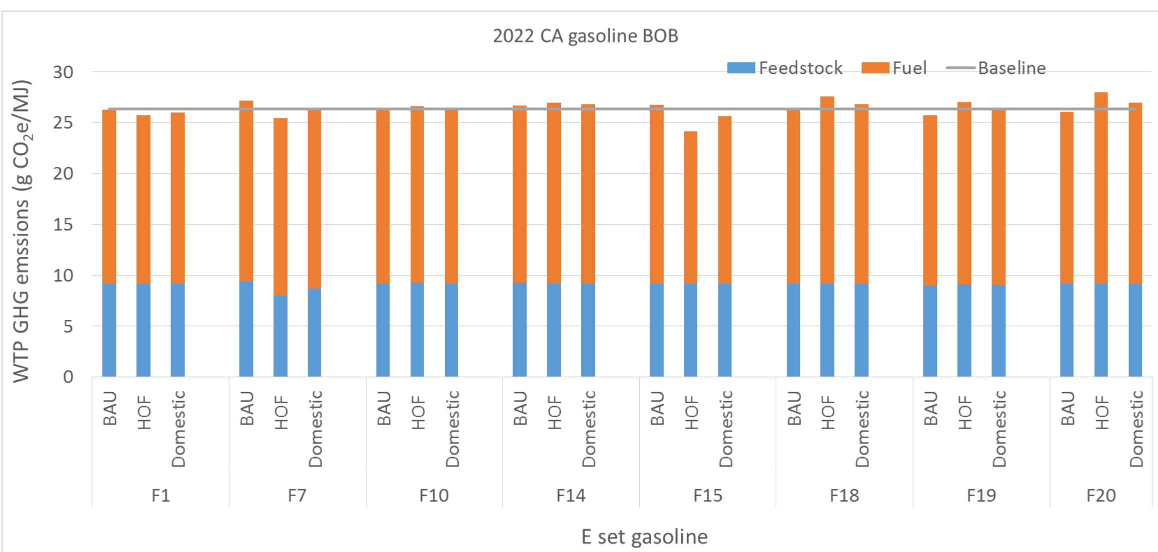


Figure 7-8. GHG Emissions of BAU and HOF Gasoline BOB Production in PADD 3 in 2022

Higher octane requirements generally lead to more refinery GHG emissions (on a per-MJ BOB basis). Two exceptions are the Fuel 15 and 19 BOB. They are blended with 30% ethanol, which introduces sufficient high octanes. The BAU pool of Fuel 15 has higher GHG emissions than baseline due to the different distribution of streams between the BAU pool and HOF pool.

In 2040, all the E set domestic gasolines are HOF gasolines. The energy use in PADD 3 and CA is shown in Figure 7-9.

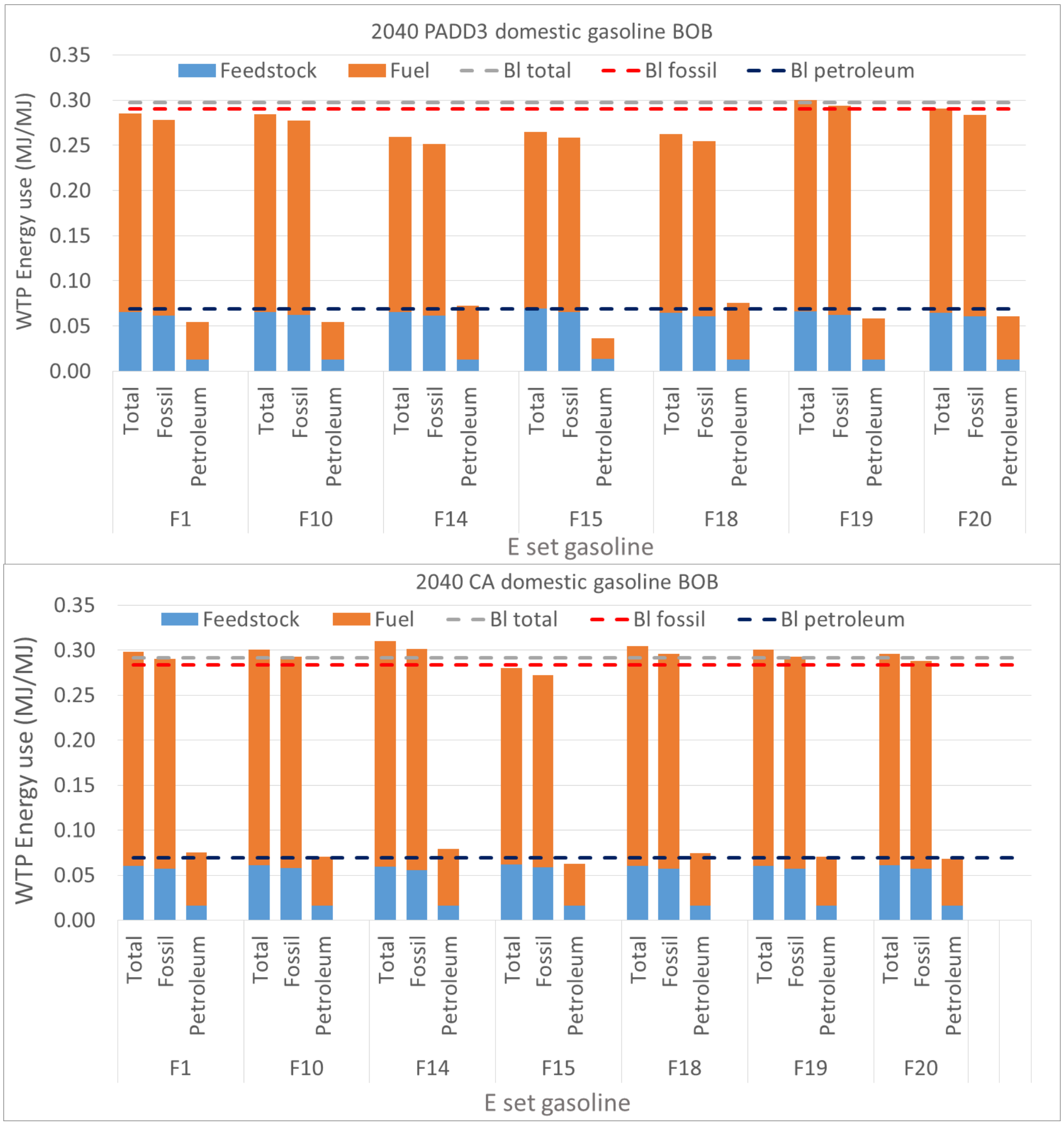


Figure 7-9. WTP Total Energy, Fossil Energy and Petroleum Energy Use for the Production of E Set Domestic Gasoline BOB in PADD 3 and in CA Refinery in 2040

In both PADD 3 and CA, Fuel 15 BOB has the lowest energy use (total, fossil and petroleum) among all E set gasoline BOBs. In PADD 3, most cases have lower energy use than baselines. It is interesting to observe that F19 and F20 BOBs in PADD 3 have slightly higher fossil energy use than other E set gasoline BOBs. This is attributed to more use of natural gasoline and butane for F19 and more use of heavy oil for F20, as discussed in Section 6. In contrast, in 2040, most cases in CA show higher energy use than baselines.

The GHG emissions of WTP gasoline BOB production in PADD 3 and CA in 2040 are shown in Figure 7-10 below.

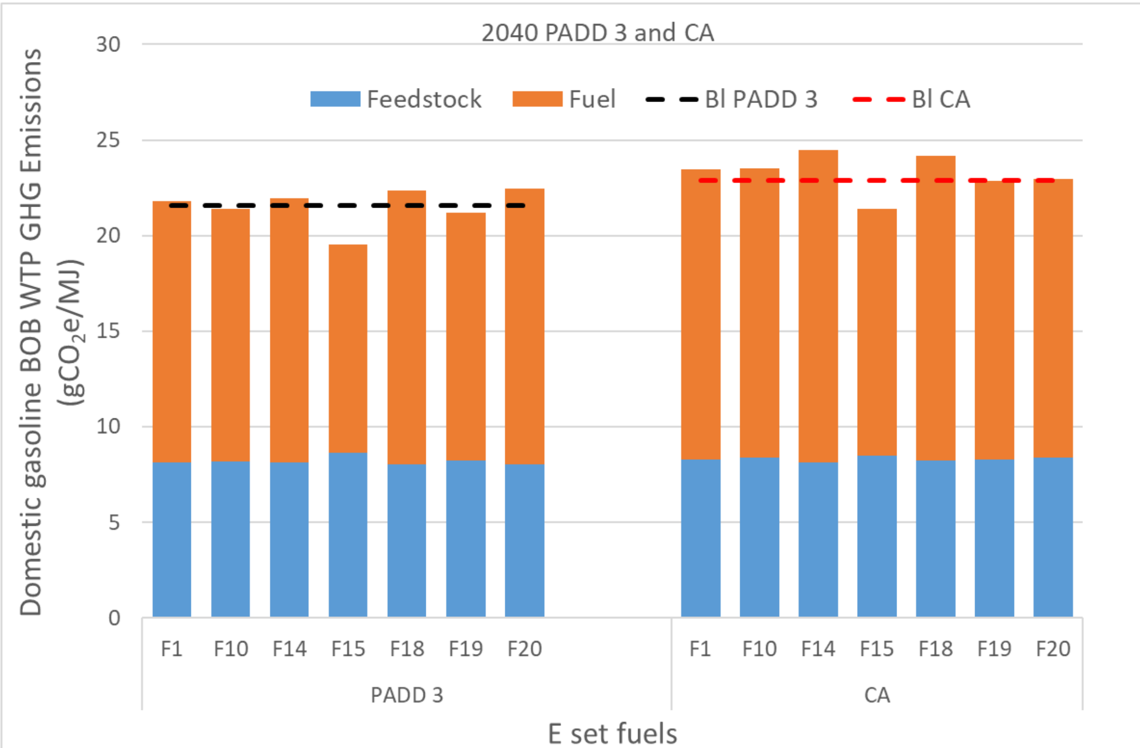


Figure 7-10. WTP GHG Emissions of Domestic Gasoline BOB Production in PADD 3 Refinery and CA Refinery in 2040

In 2040, for both PADD 3 and CA, Fuel 15 shows the lowest GHG emissions for gasoline BOB production compared with the other E set fuels. In PADD 3, it is worth noting that both Fuel 14 and Fuel 18 show higher GHG emissions but lower fossil energy use than baseline. This is because although GHG emissions, by and large, track fossil energy use directionally, they do not track fossil energy use exactly, since the three fossil sources—petroleum, natural gas and coal—have different carbon intensities per energy unit.

From 2022 to 2040, in PADD 3, WTP GHG emissions for E set gasoline pool BOB increase, caused by a slight increase in the fuel stage due to crude slate change. In CA, the WTP GHG emissions of E set gasoline BOB decrease, due to less energy use in the fuel stage. The decrease stems from a decrease in crude input combined with an increased input of "heavy" (unfinished oil purchased from other refineries).

7.1.3 WTP Analysis of Configuration Refinery Base Cases Gasoline BOBs

WTP energy use and GHG emissions for the production of gasoline BOBs for configuration refinery base cases are shown in Figure 7-11 and Figure 7-12.

As expected, for gasoline BOB production, most of the energy used is from fossil sources. The energy use increases in the order CRK < LtCOK < COKHCK < HvyCOK. The differences stem from both the feedstock stage and the fuel stage. Changes in the feedstock stage are caused by the different energy intensity associated with different crude recovery (e.g., oil sand recovery is more energy intensive than conventional crude recovery). The change in the fuel stage is caused by differing energy use in refining processes. Among the fossil energy sources, natural gas and coal use is between 50% and 74% of the total, increasing as refinery complexity increases. This is consistent with the increased natural gas use in more sophisticated refineries, largely driven by hydrogen demand.

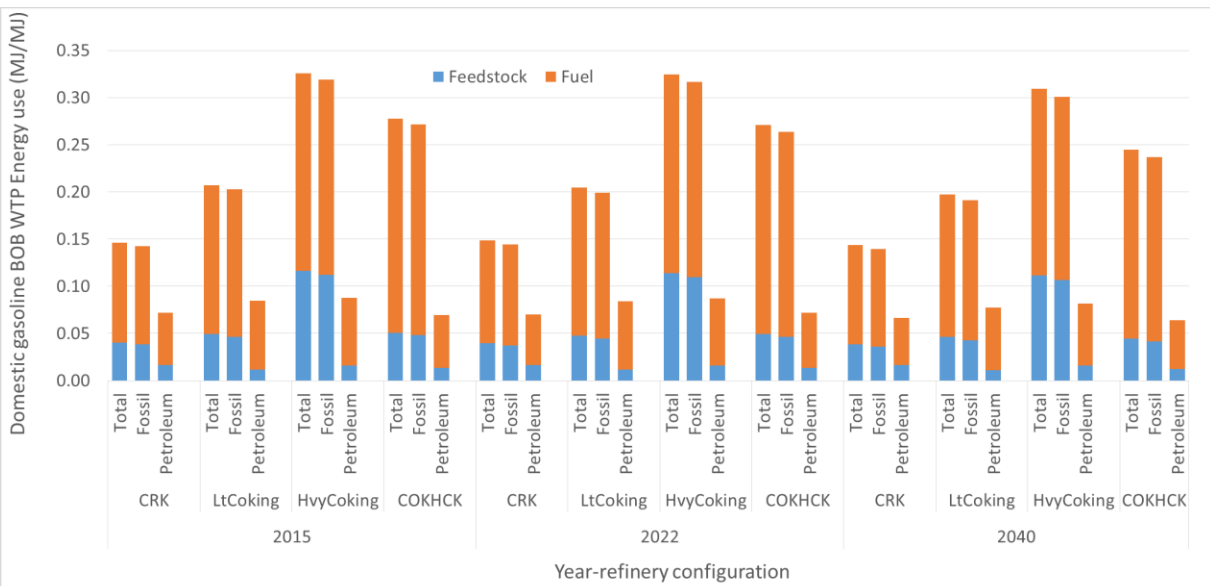


Figure 7-11. Energy Use for the WTP Production of Gasoline BOBs of Configuration Refinery Base Cases

As noted in Section 5, different refinery configurations process different crude slates and have different process units, resulting in different GHG emissions. For each year studied, the GHG emissions from BOB feedstock (crude recovery and transportation) in each configuration refinery vary significantly, due to their very different crude slate mixes. Although both HvyCOK and COKHCK (CA) configurations use heavy crude with low API, the different crude source (oil sands for the former and conventional sources for the latter) differentiate the two configurations in GHG emissions. The GHG emissions of the BOB fuel stage of the base case configuration refineries increase with increasing refinery complexity (See Figure 7-12). This is attributable to increased natural gas use by the more complex refineries, mostly for hydrogen production via SMR.

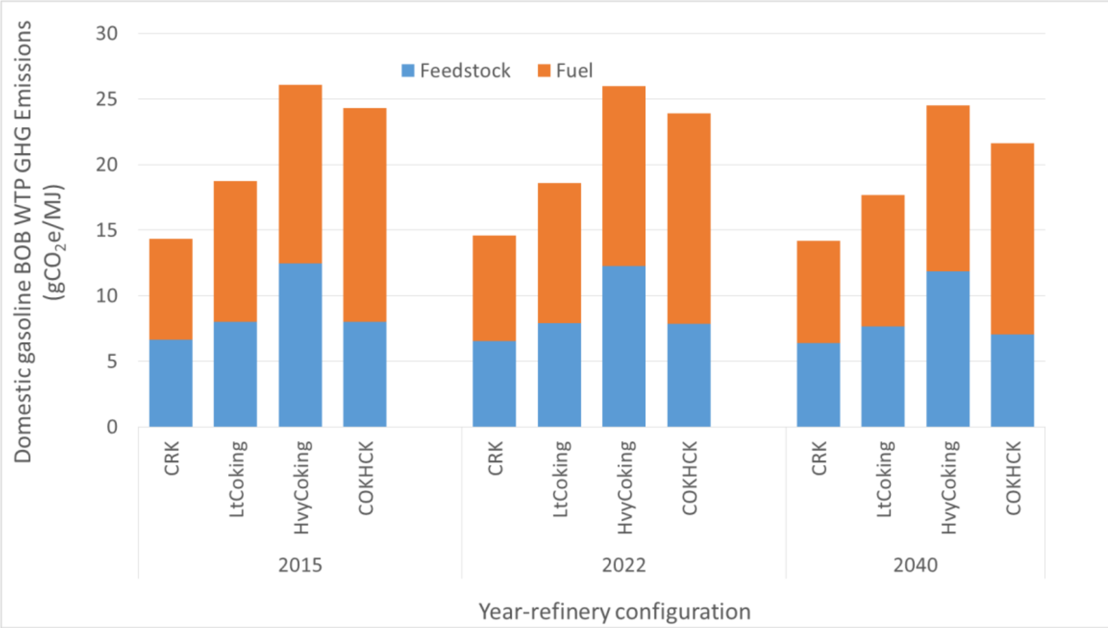


Figure 7-12. GHG Emissions for the WTP Production of Gasoline BOBs for Configuration Refinery Base Cases

7.1.4 WTP Analysis of E Set Domestic Gasoline BOBs Produced in Configuration Refineries

For all the configuration cases of E set fuels, the GHG emissions associated with gasoline BOB production were calculated using the same crude slates as the configuration base case models.

The energy use of producing BOB gasoline for the BAU pool and the HOF pool is shown in Figure 7-13 to Figure 7-16 below.

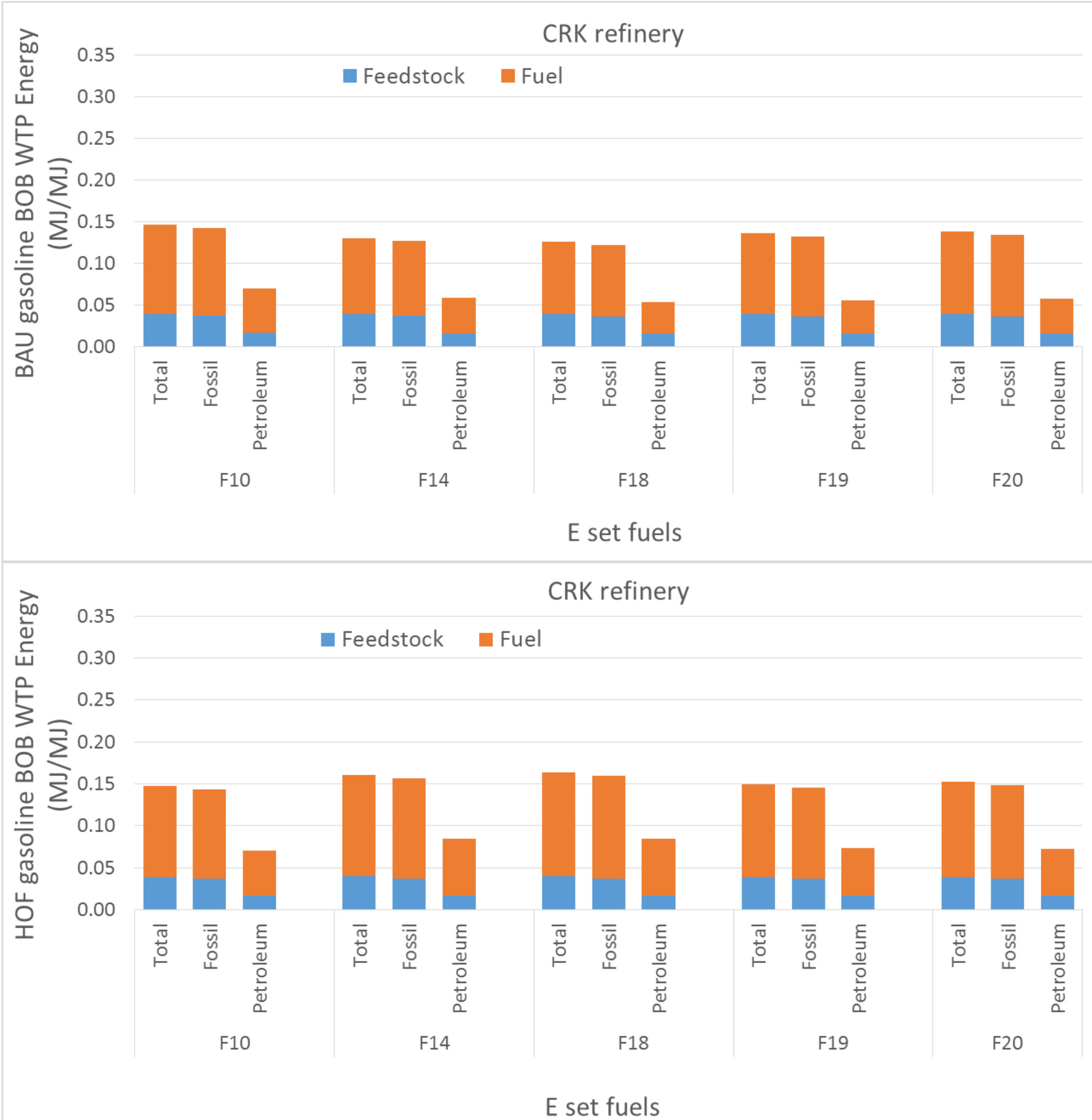


Figure 7-13. WTP Energy Use for the Production of E Set BAU Gasoline BOB and HOF Gasoline BOB in CRK Configuration Refinery in 2022

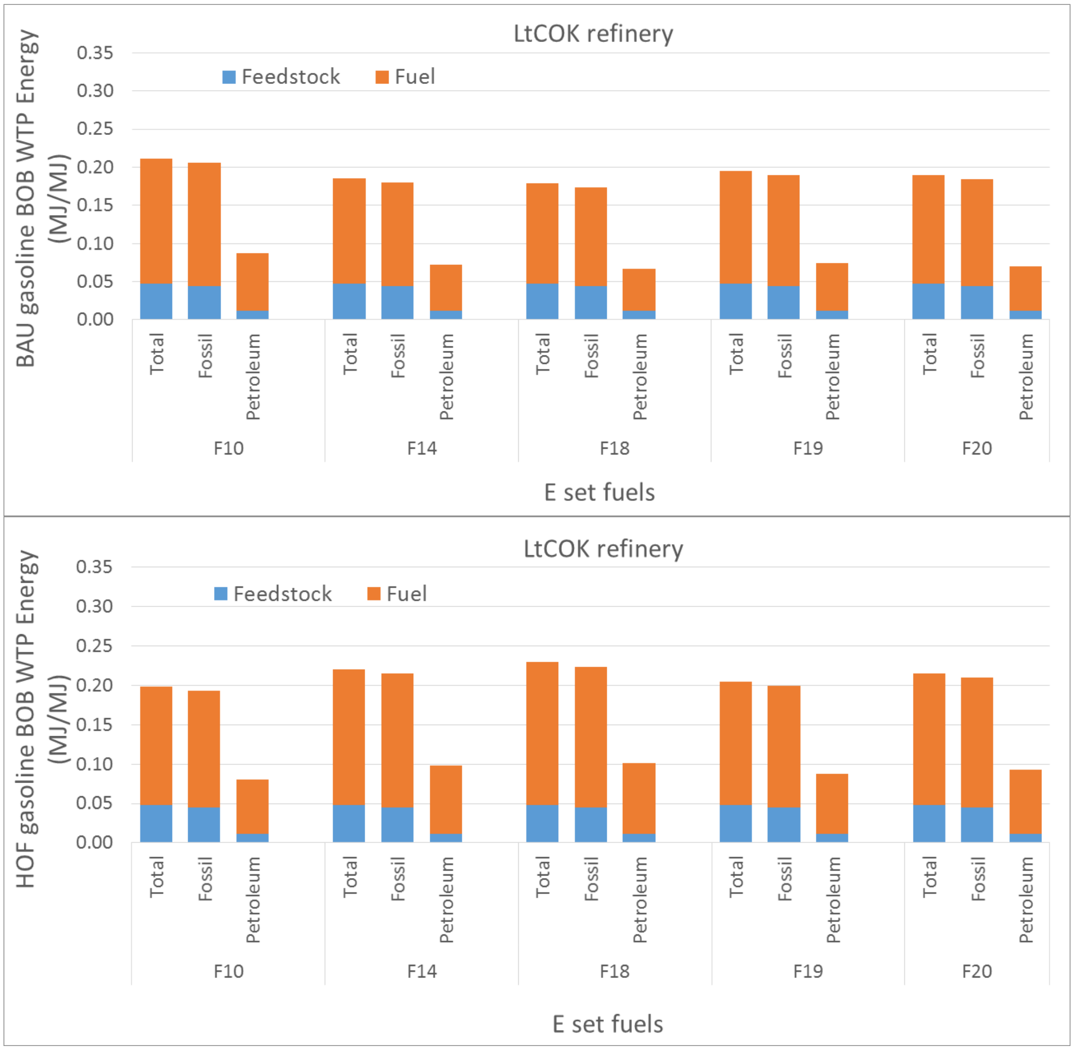


Figure 7-14. WTP Energy Use for the Production of E Set BAU Gasoline BOB and HOF Gasoline BOB in LtCOK Configuration Refinery in 2022

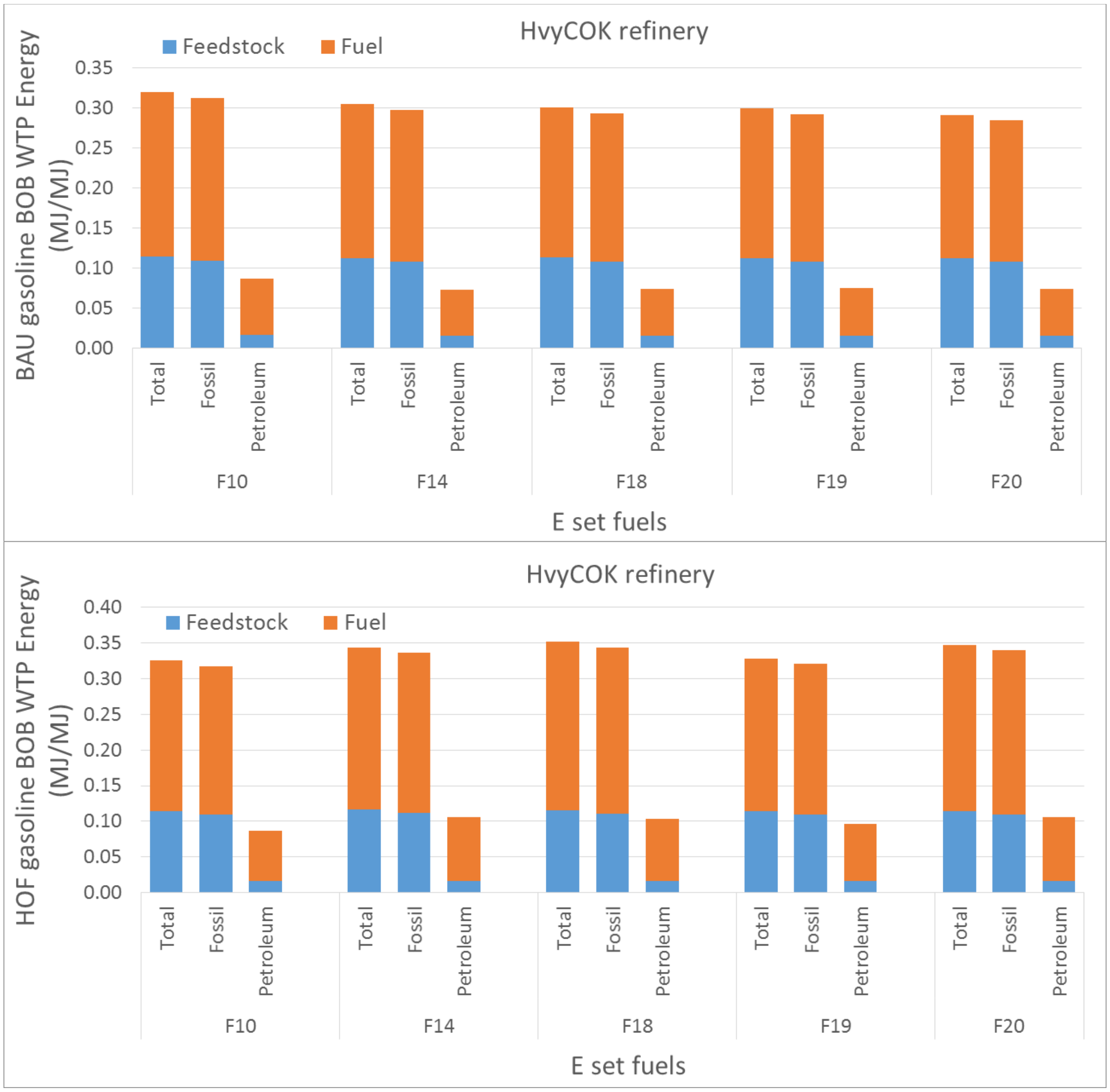


Figure 7-15. WTP Energy Use for the Production of E Set BAU Gasoline BOB and HOF Gasoline BOB in HvyCOK Configuration Refinery in 2022

As with configuration refinery base cases, most of the energy used for gasoline BOB production is from fossil sources. The energy use increases in the order CRK < LtCOK < COKHCK < HvyCOK, attributable to differences in crude recovery energy intensity in the feedstock stage and different energy use in refining operations. A comparison of BAU gasoline energy use to HOF gasoline energy use is different for each fuel set, depending on the specific refinery operation's response to producing each high-octane E set fuel and the subsequent distinctive component shares in each gasoline pool. The detailed energy input sources (crude, natural gas, electricity, butane, etc.) for BAU and HOF gasoline BOB production were shown as gasoline production energy intensity in Section 6. A comparison of energy use for E set domestic gasoline BOB with baseline is shown in Figure 7-17 to Figure 7-20 below.

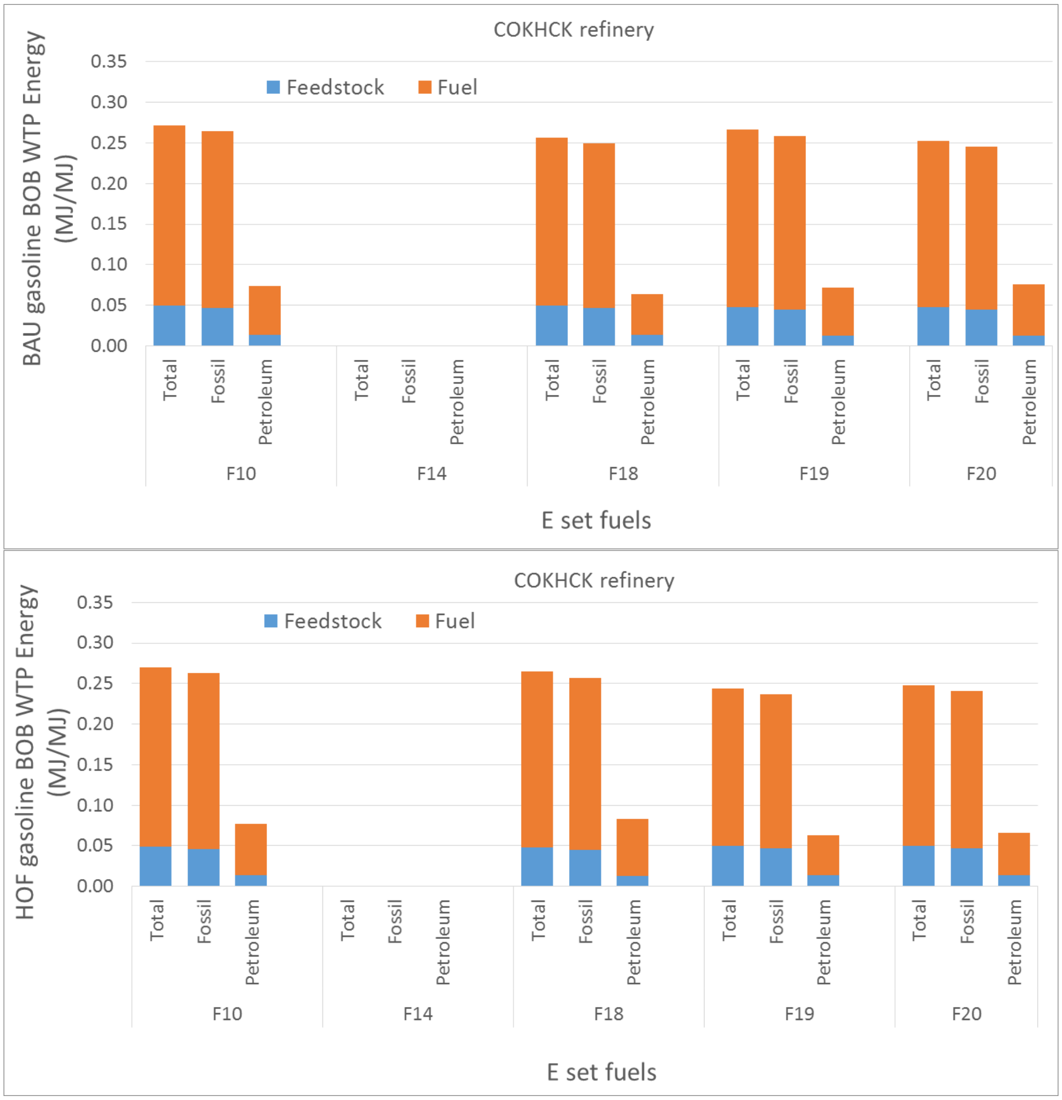


Figure 7-16. WTP Energy Use for the Production of E Set BAU Gasoline BOB and HOF Gasoline BOB in COKHCK Configuration Refinery in 2022

In 2022, for each E set gasoline, combining the energy use for BAU gasoline BOB production and HOF gasoline BOB production results in the energy use for domestic gasoline BOB production, shown in Figure 7-17 to Figure 7-20. For all four configuration refineries, Fuel 10 and Fuel 14 cases have an energy uses for gasoline BOB production similar to baselines, while Fuel 18, Fuel 19 and Fuel 20 cases show lower energy uses than baselines. The LP modeling of F14 in COKHCK did not yield a feasible solution.

The results indicate that the gasoline BOB WTP GHG emissions (crude recovery, transportation, refinery operation and T&D) are strongly dependent on configuration and less influenced by the targeted fuel product properties (high octane numbers), shown in Figure 7-21.

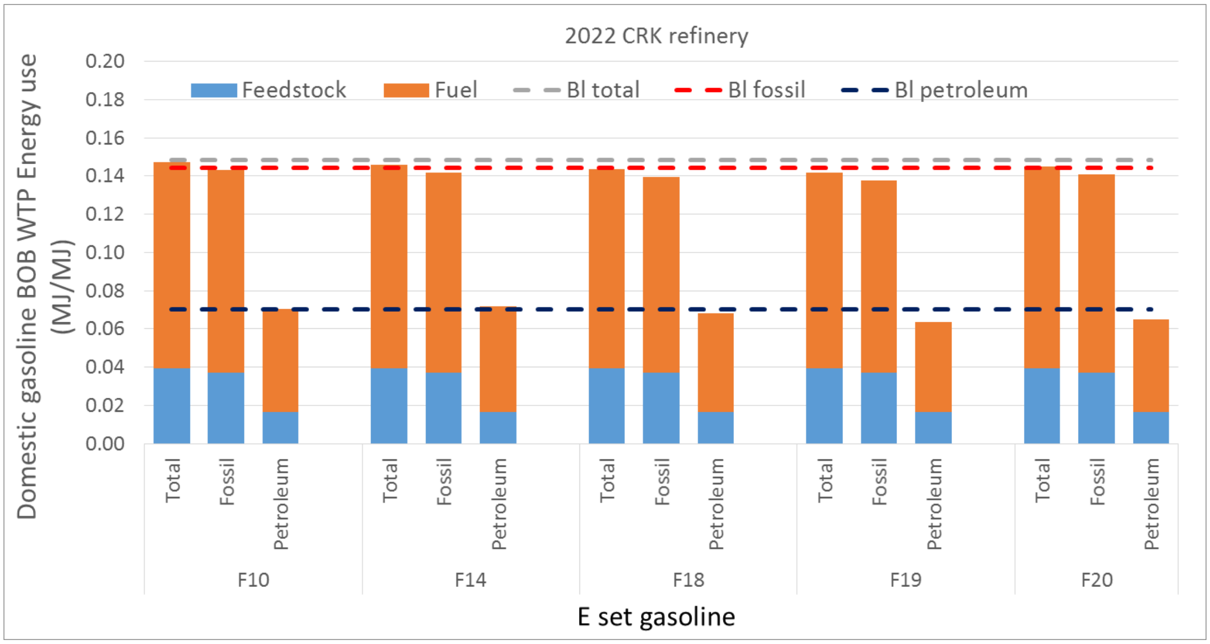


Figure 7-17. WTP Energy Use for the Production of E Set Domestic Gasoline BOBs in CRK Configuration Refineries in 2022

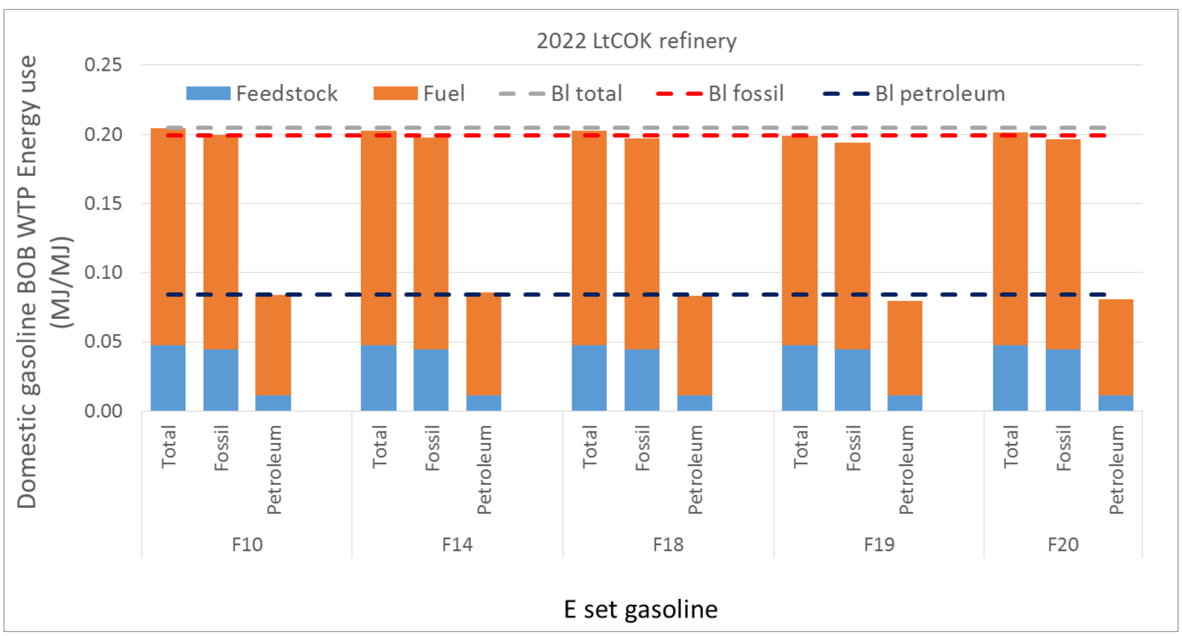


Figure 7-18. WTP Energy Use for the Production of E Set Domestic Gasoline BOBs in LtCOK Configuration Refineries in 2022

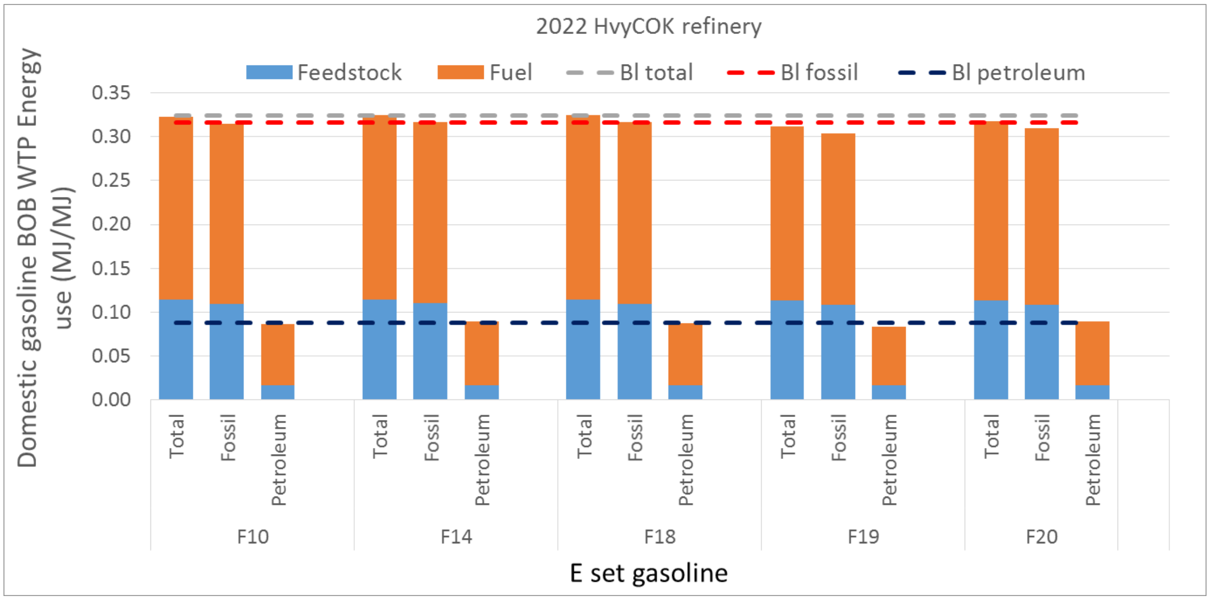


Figure 7-19. WTP Energy Use for the Production of E Set Domestic Gasoline BOBs in HvyCOK Configuration Refineries in 2022

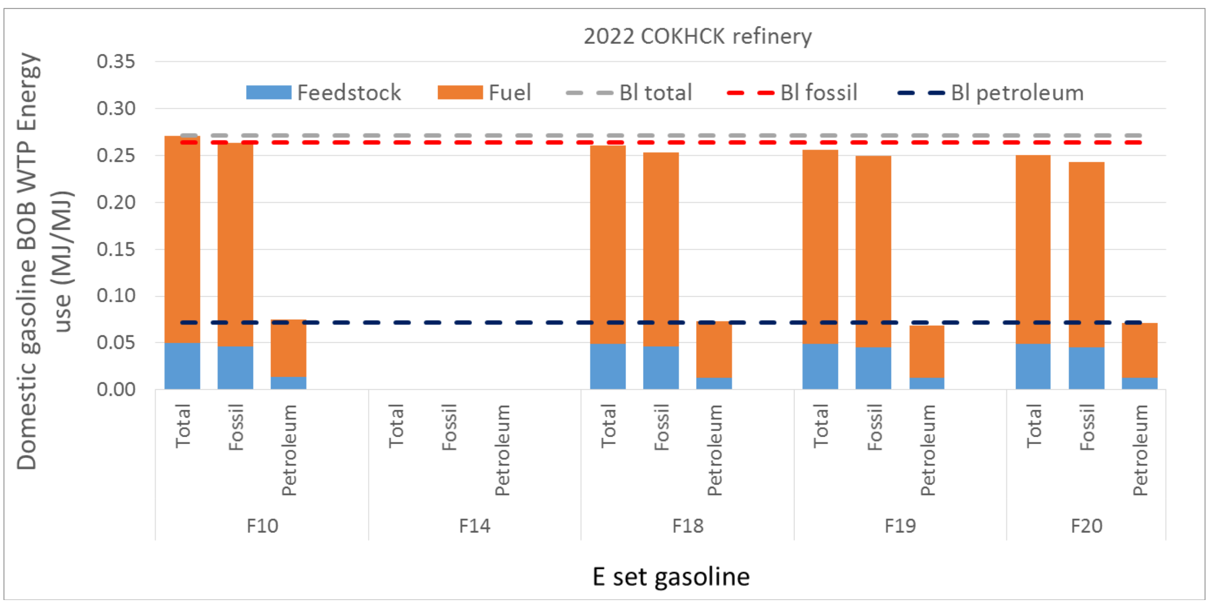


Figure 7-20. WTP Energy Use for the Production of E Set Domestic Gasoline BOBs in COKHCK Configuration Refineries in 2022

Figure 7-21. WTP GHG Emission for E set Domestic Gasoline Pool BOBs Production in Configuration Refineries in 2022

Consistent with the energy use, the heavy coking configuration has the highest GHG emissions for the feedstock stage, due to more processing of carbon-intensive oil sands. For the fuel stage, the gasoline BOB production in the COKHCK configuration (CA) has the highest GHG emissions from refineries compared with the others because it is the most complex configuration, with more energy intensive units and high hydrogen demand.

It is worth noting that for each E set fuel, the production of BAU gasoline BOB has lower GHG emissions than baseline, while the production of HOF gasoline pool BOB produces more GHG. However, after being combined, the resultant domestic gasoline BOB has GHG emissions similar to or slightly lower than baseline. This implies that although the BAU gasoline BOB and HOF gasoline BOB vary significantly in components, the difference of the combined domestic gasoline BOB, dictated by refinery unit capacity or refinery configuration, is less pronounced.

In 2040, all domestic gasolines are HOF, and their BOB production energy uses, in different configuration refineries, are shown in Figure 7-22 to Figure 7-25 below.

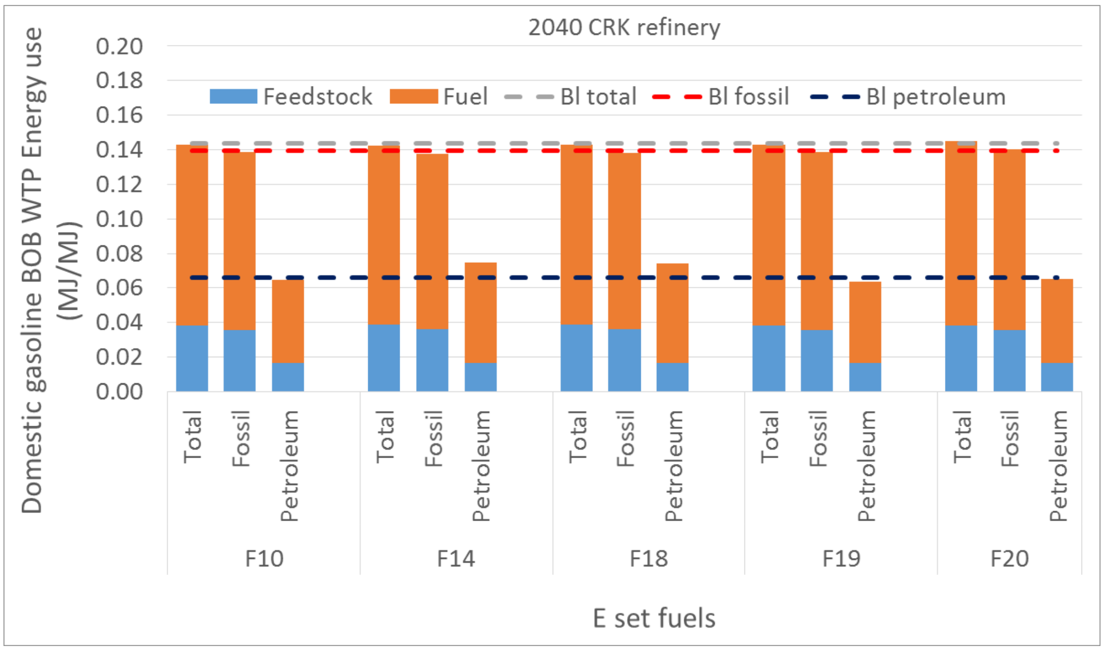


Figure 7-22. WTP Energy Use for the Production of E Set Domestic Gasoline BOB in CRK Configuration Refineries in 2040

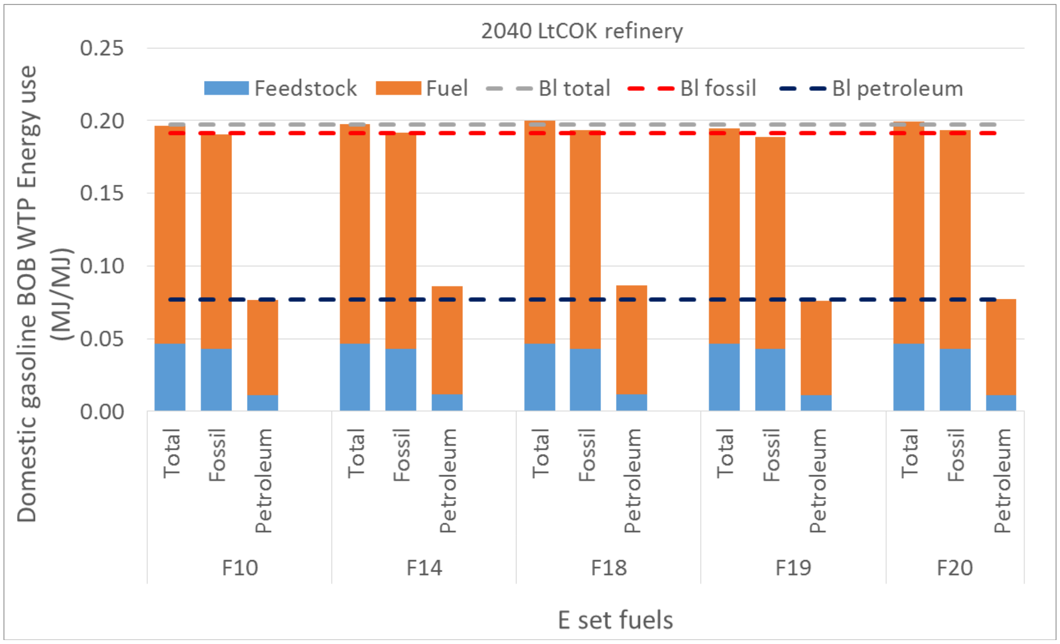


Figure 7-23. WTP Energy Use for the Production of E Set Domestic Gasoline BOB in LtCOK Configuration Refineries in 2040

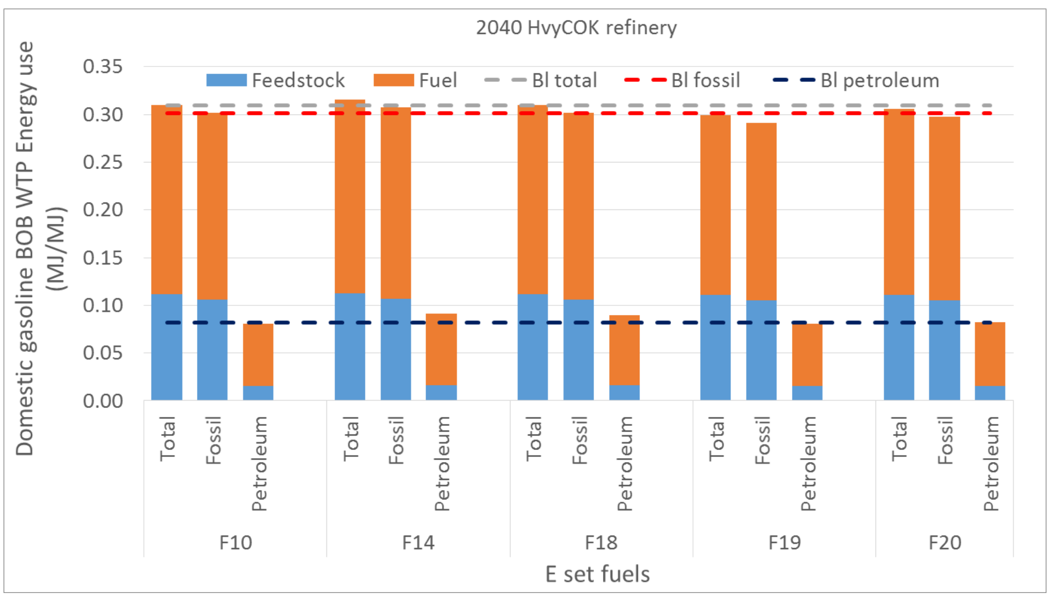


Figure 7-24. WTP Energy Use for the Production of E Set Domestic Gasoline BOB in HvyCOK Configuration Refineries in 2040

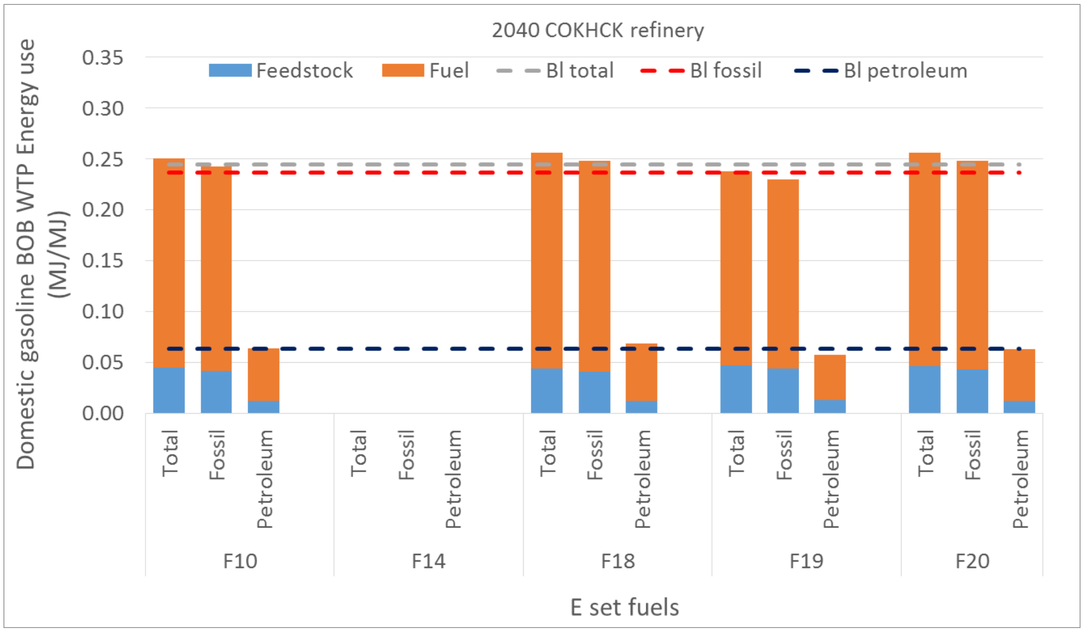


Figure 7-25. WTP Energy Use for the Production of E Set Domestic Gasoline BOB in COKHCK Configuration Refineries in 2040

Compared with 2022 cases, the WTP energy use for E set domestic gasoline BOB production in each configuration refinery in 2040 decreases slightly. Overall, Fuel 14 has slightly higher energy use than baseline in most cases, while F19 has lower energy use than baseline. For F18 and F20, the comparison of the energy use for BOB production to baseline varies for each case, depending on refinery configuration and fuel.

The WTP GHG emissions for the production of E set gasoline BOBs in 2040 are shown in Figure 7-26 below.

WTP GHG emissions for producing E set domestic gasoline BOB increase with increasing refinery configuration complexity. Interestingly, with increasing refinery complexity, more cases show higher GHG emissions than baselines. In the CRK refinery, all E set cases show GHG emissions similar to or lower than CRK configuration baseline. For the LtCOK and HvyCOK refinery, F14 and F18 show higher GHG emissions than baselines. For the COKHCK refinery, Fuel 14 cannot be produced (infeasibility of LP modeling solution), and F10, F18 and F20 show higher GHG emissions than baselines. Overall, from 2022 to 2040, although the absolute GHG emissions decrease for all cases, their changes compared to baselines increase.

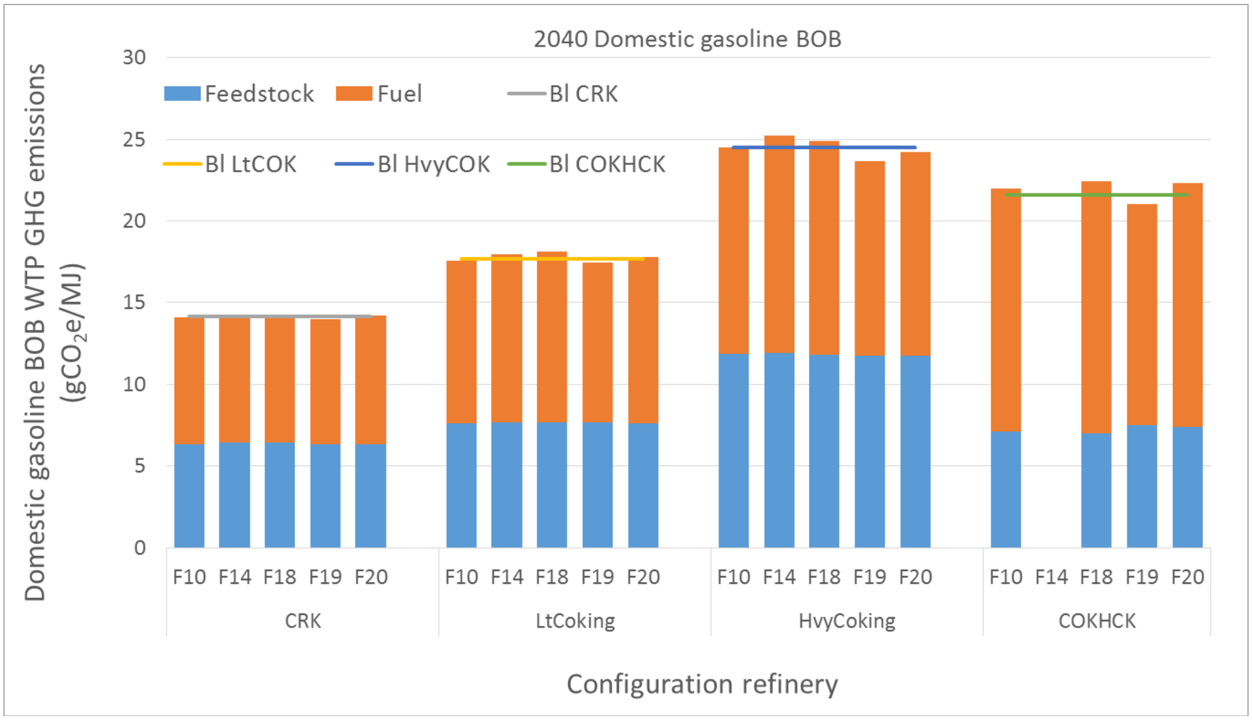


Figure 7-26. WTP GHG Emissions for Domestic Gasoline BOB Production in Configuration Refineries in 2040

7.2 WTP Analysis of BR Set Gasoline BOBs

The energy use and GHG emissions for producing BR set gasoline BOBs were investigated for both aggregate and configuration refineries, in 2022 and 2040. The results are discussed below.

7.2.1 WTP Analysis of BR Set Gasoline BOBs in Aggregate Refineries

The production of BR set fuels were modeled in PADD 2 and PADD 3 refineries in 2022 and 2040. The LP modeling of the BR set fuels in CA did not yield any feasible solutions, owing to the more stringent aromatic constraints in CA.

Energy use for the production of BR BAU gasoline BOB, HOF gasoline BOB and domestic gasoline BOB in 2022 is shown in Figure 7-27 below, compared with baselines.

BR set gasoline BOBs have similar energy use at the feedstock stage and are in line with base cases, while their energy use at the fuel stage (refining process) differ for each case. For both PADD 2 refinery and PADD 3 refinery cases, the BAU gasoline BOBs of BR1-T and BR4-T have higher energy use than baselines. The energy use of HOF gasoline BOBs shows the opposite trend. This is consistent with their energy intensity results, shown in Section 6. Combining BAU gasoline BOB and HOF gasoline BOB energy use results in the energy use for producing BR domestic gasoline BOBs. All the BR set domestic gasoline BOBs, either in PADD 2 or PADD 3, show less energy use than baselines.

A comparison of GHG emissions for gasoline BOBs production for BR/BR-T fuel is shown in Figure 7-28 below.

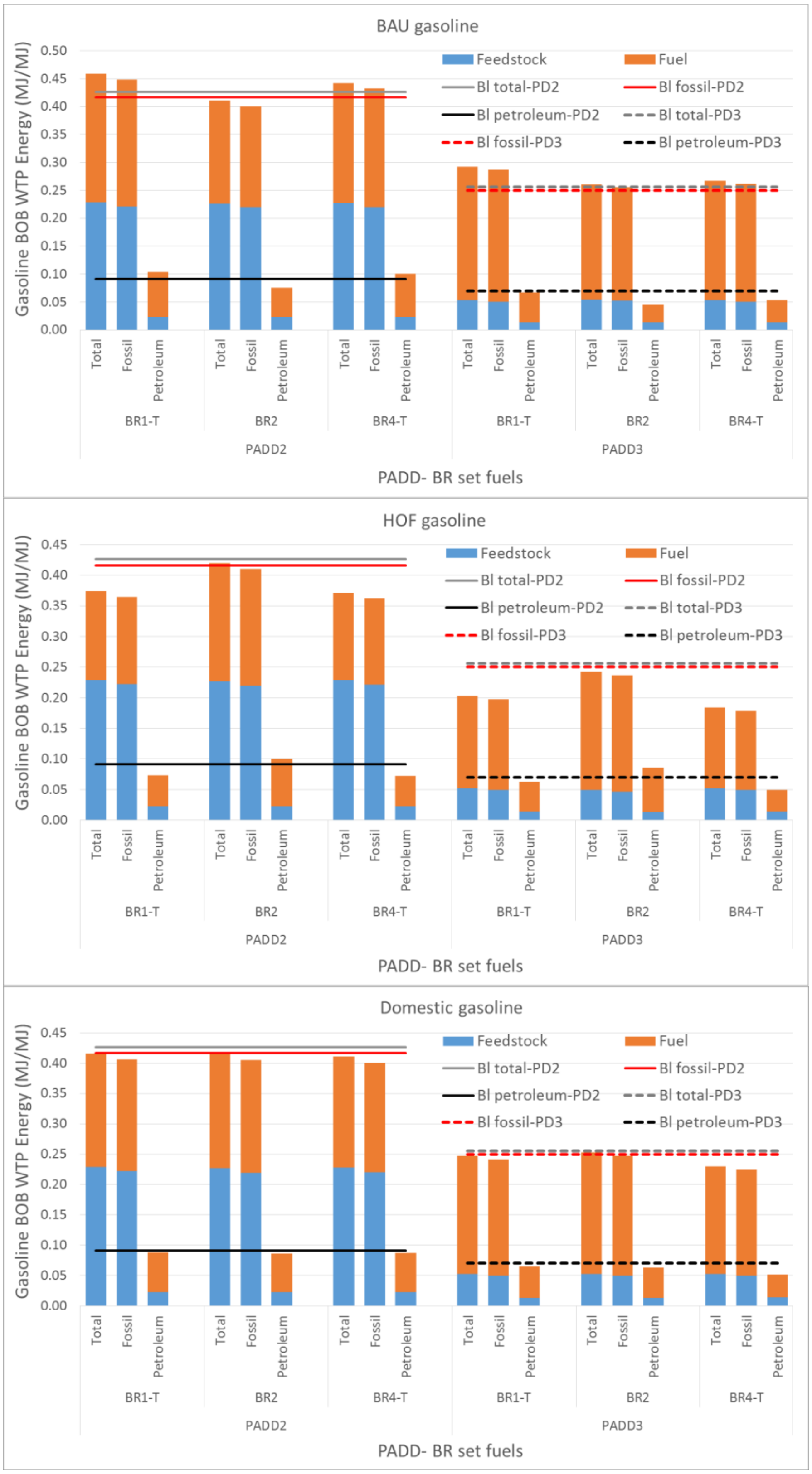


Figure 7-27. Energy Use for the Production of BR Set Gasoline BOBs (BAU, HOF and domestic) in PADD 2 and PADD 3 Refineries in 2022

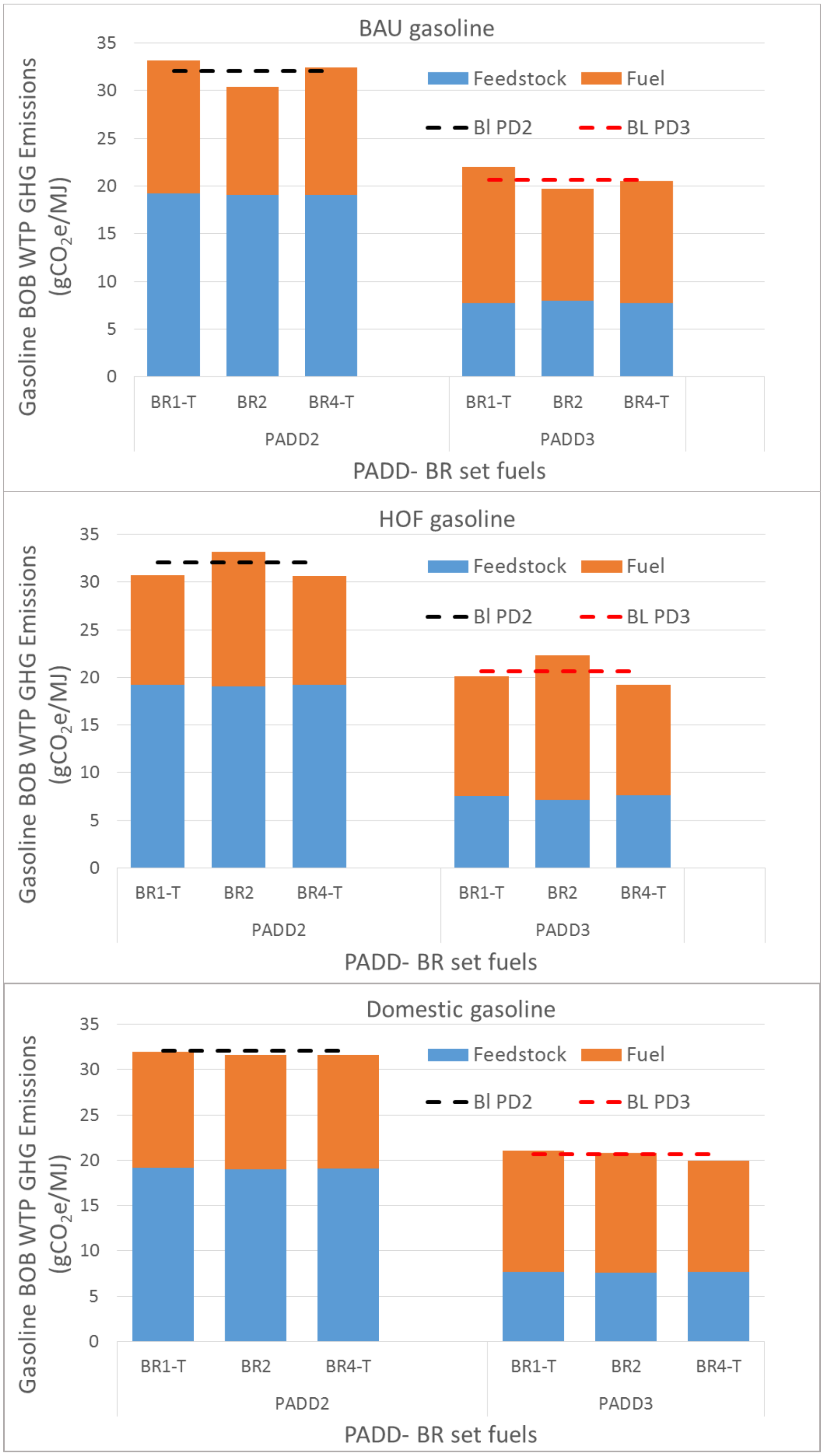


Figure 7-28. GHG Emission Comparison of Gasoline BOBsProduced for BR/BR-T Set Fuels in 2022

As expected, the BOBs produced in PADD 2 had much higher GHG emissions than those in PADD 3, due to the use of oil sands in the feedstock stage. The fuel production stage in PADD 3 had slightly higher GHG emissions than in PADD 2, owing to the higher refinery complexity in PADD 3.

The GHG emissions for producing BR gasoline BOBs show trends similar to energy use. BAU gasoline BOBs for BR1-T and BR4-T have higher GHG emissions than baselines, while the HOF gasolines BOBs have lower GHG emissions. Although a comparison of BAU to HOF gasolines varies for each BR set fuel, the combined domestic gasoline BOBs have values similar to baselines.

In 2040, all domestic gasolines are HOF. The energy use for 2040 cases is shown in Figure 7-29 below.

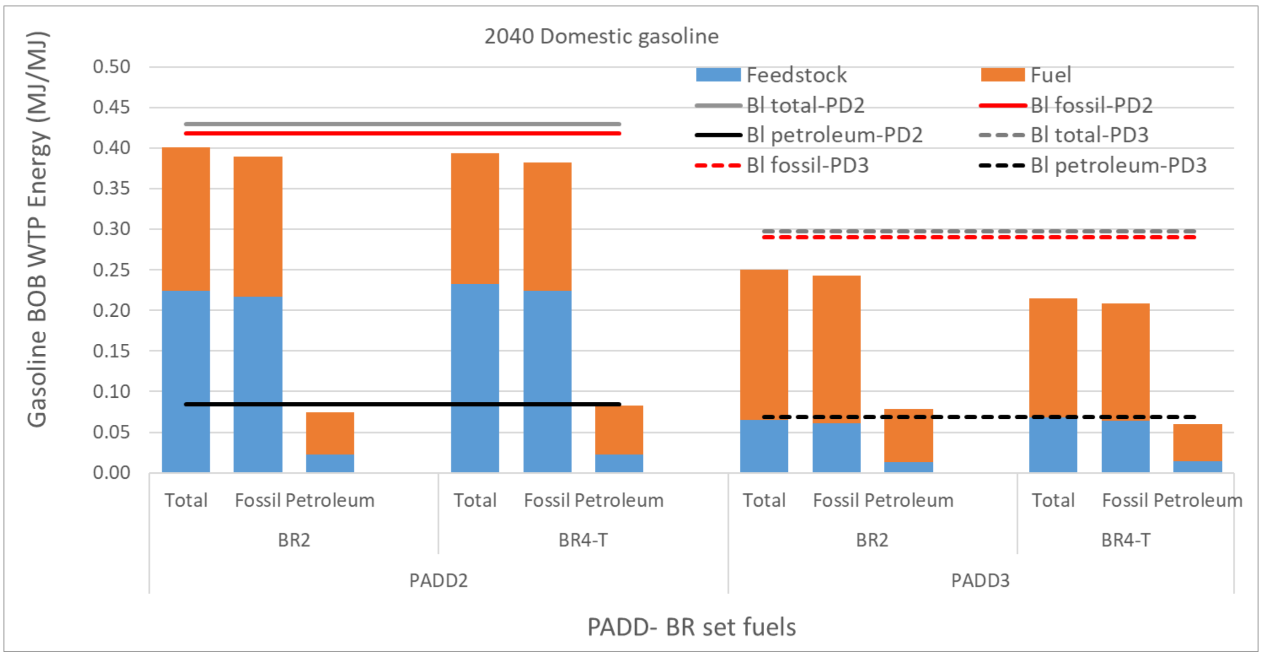


Figure 7-29. Energy Use for the Production of BR Set Domestic Gasoline pool BOBs in PADD 2 Refinery and PADD 3 Refinery in 2040

In 2040, all BR set BOBs have lower energy use than baselines, and their divergence from baseline is greater than in 2022.

The GHG emissions for producing BR domestic gasoline BOBs are shown in Figure 7-30 below.

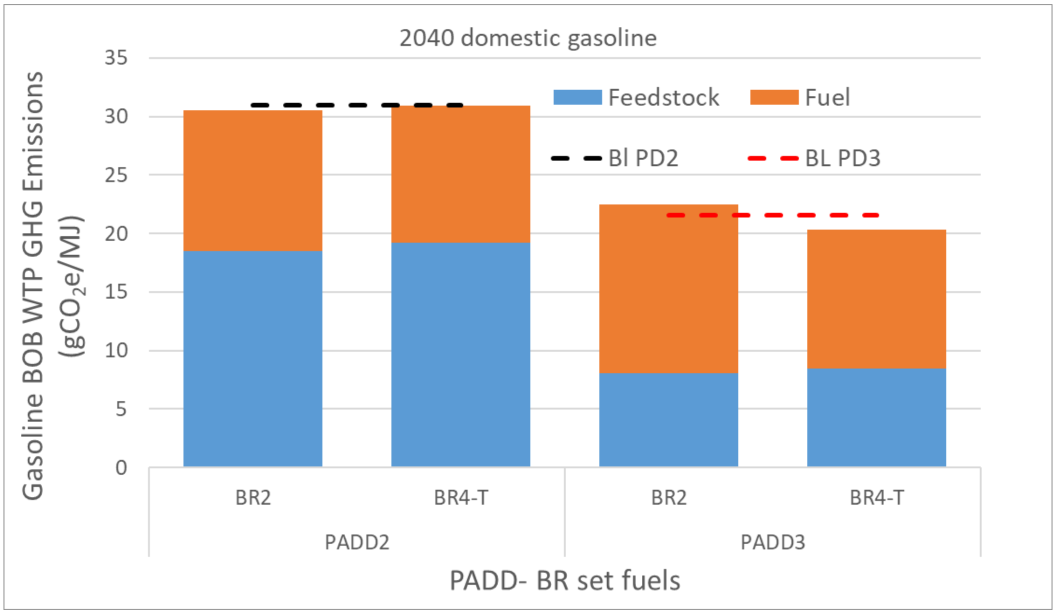


Figure 7-30. GHG Emissions for Producing BR Domestic Gasoline BOBs in PADD 2 Refinery and PADD 3 Refinery

As was the case with energy use, more BR gasoline BOBs show lower GHG emissions than baselines, except for BR2 production in PADD 3. Again, the GHG emissions only track fossil energy use directionally, as different fossil sources (petroleum, natural gas and coal) have different carbon intensities. From 2022 to 2040, for both BR2 BOBs and BR4-T BOB production, the GHG emissions in PADD 2 decrease while the GHG emissions in PADD 3 increase.

<u>7.2.2 WTP Analysis of Configuration Refinery BR Set Fuel Cases</u>

The WTP results of BR set gasoline BOBs in only three configuration refineries — CRK, LtCOK, and HvyCOK—were investigated, as the LP modeling of BR BOBs in COKHCK refinery cannot yield any feasible solutions. The energy use for producing BR set gasoline BOBs in configuration refineries is shown in Figure 7-31.

In 2022, the energy use for producing each BR gasoline BOB increases with increasing refinery complexity, in both the feedstock stage and the fuel stage. For all three refinery configurations, the production of BR4-T uses more energy than that of BR2-T due to the higher octane number demand. For all three configuration refineries, the BR2-T set BAU gasoline BOB production uses less energy than baselines while the HOF gasoline BOB production uses more energy than baseline. However, the energy use of BR4-T BOB production compared with baseline varies with refinery configuration and energy category (total, fossil or petroleum). As a result, for both BR2-T and BR4-T, the combined BR domestic gasoline BOBs have lower total energy and fossil energy use but higher petroleum energy use than baselines.

GHG emissions for BR gasoline BOB production are shown in Figure 7-32 below.

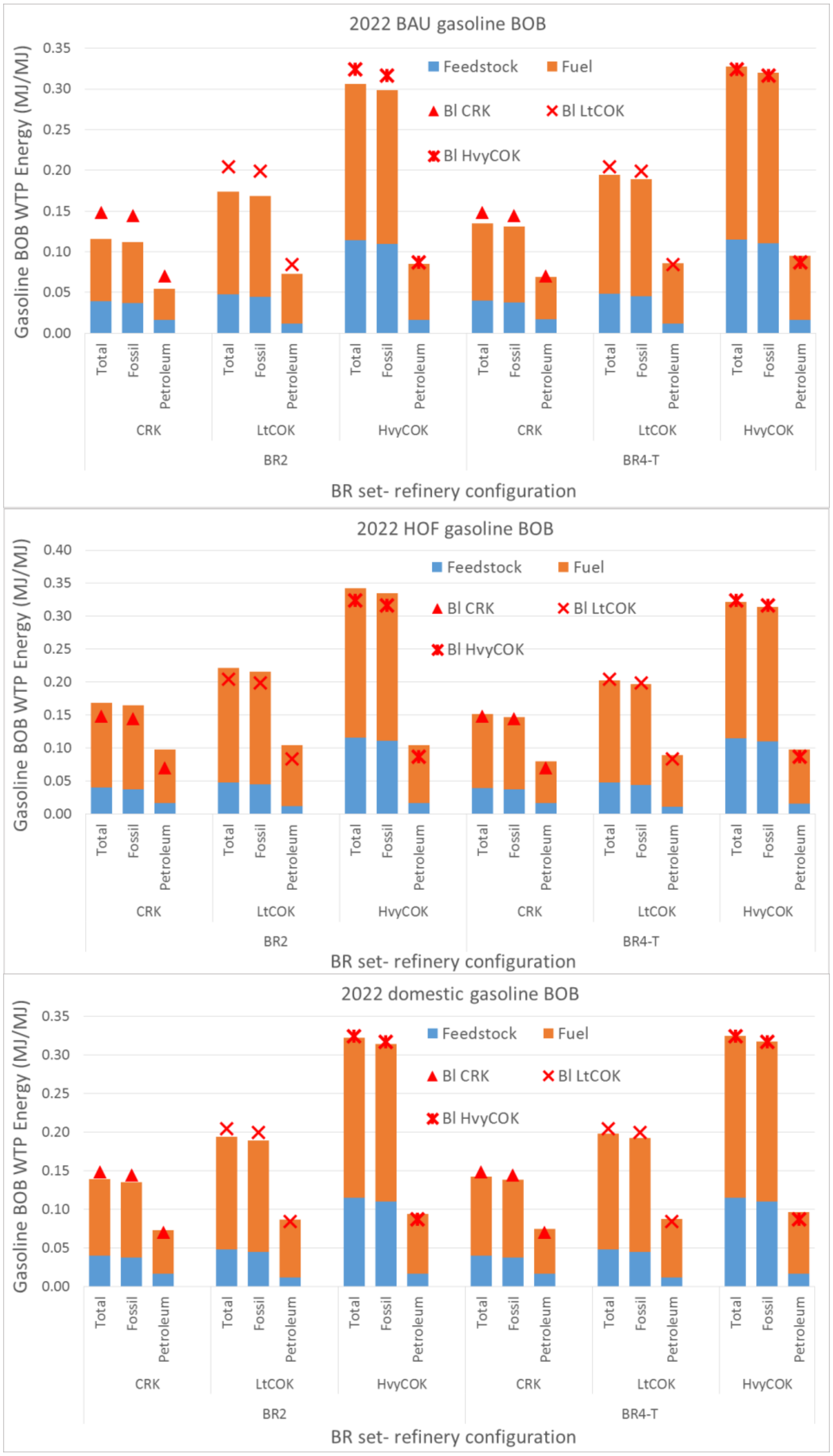


Figure 7-31. Energy Use to Produce BR Set Gasoline (BAU, HOF and domestic) BOBs in Configuration Refineries in 2022

Figure 7-32. GHG Emissions for Producing BR Set Domestic Gasoline BOBs in Configuration Refineries in 2022

In 2022, the BAU GHG emissions and HOF GHG emissions for each BR or BR-T set gasoline are similar in the feedstock stage (mainly crude recovery), but differ in the fuel stage (refinery operation and energy input upstream). The noticeable difference in GHG emissions between BAU and HOF production is not surprising given their very different component shares, shown in Section 5.

Consistent with the energy use trend, the domestic BR2 gasoline BOBs have slightly lower GHG emissions than baselines for all three configuration refineries. With higher GHG emissions than the BR2 domestic gasoline BOBs, the BR4-T domestic gasoline BOBs are close to baselines for CRK and LtCOK refineries, but show slightly higher GHG emissions in the HvyCOK refinery.

The results of BR domestic (all HOF) BOB analysis in 2040 are shown in Figure 7-33 below.

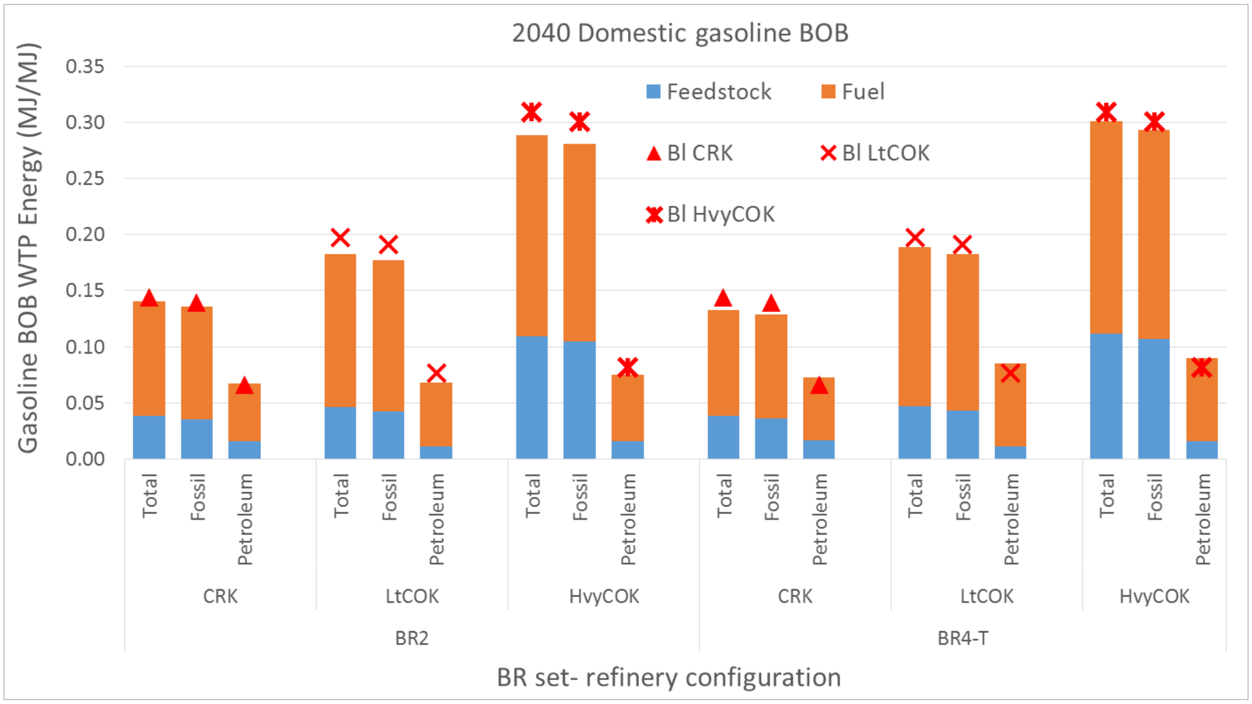


Figure 7-33. Energy Use for Producing BR Set Domestic Gasoline BOBs in Configuration Refineries in 2040

In 2040, both BR2 and BR4-T cases show lower total energy use and lower fossil energy use than baselines. At the same time, BR2 cases have lower petroleum energy use than baselines while BR4-T cases show higher petroleum energy use than baselines.

The GHG emissions for BR domestic gasoline BOB production are shown in Figure 7-34.

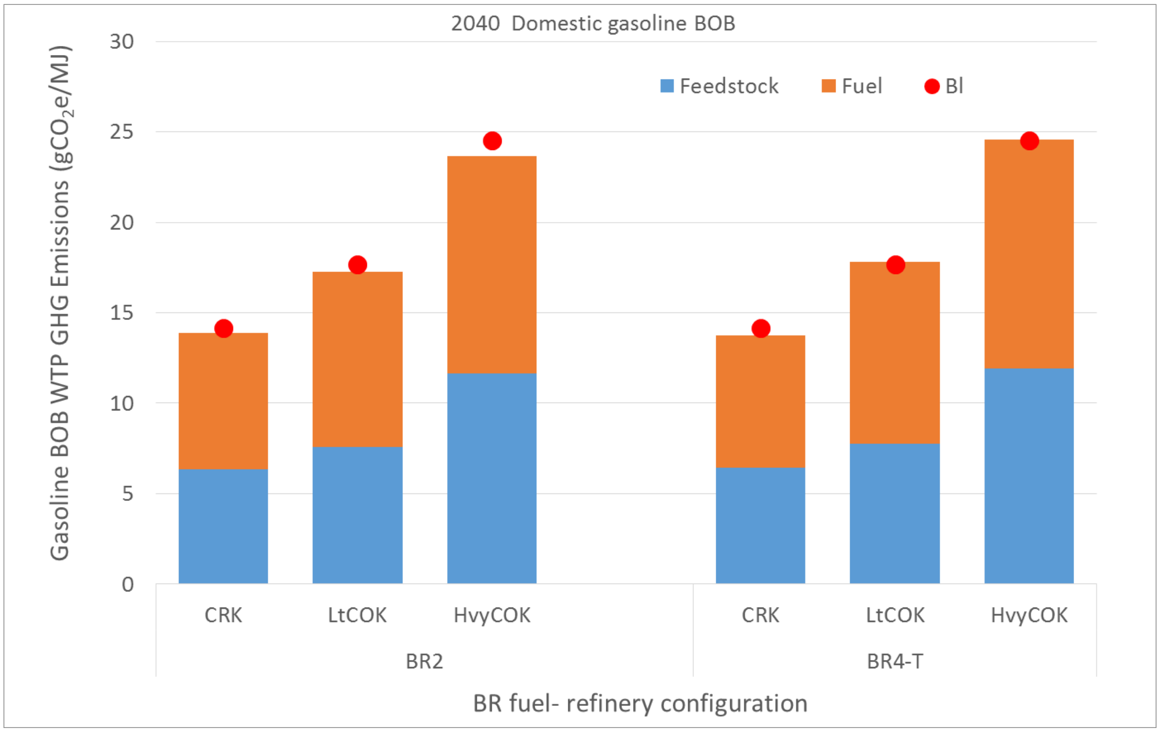


Figure 7-34. GHG Emissions for Producing BR Set Domestic Gasoline BOBs in Configuration Refineries in 2040

In 2040, the GHG emissions gap between the BR gasoline BOBs production and baselines is narrowed. Most cases show GHG emissions similar to baselines, except for BR2 BOB produced in the HvyCOK configuration, which has noticeable decreases. Unlike the cases in 2022, BR4-T BOB production shows higher GHG emissions only for the HvyCOK configuration and lower GHG emissions for the CRK and LtCOK refinery configurations.

As expected, the GHG emissions for both BR set BAU and HOF gasoline BOB increase with increasing configuration complexity. From 2022 to 2040, GHG emissions for BR set BOBs produced in all configuration refineries decreased along the WTP stages. Compared with the baseline BOB for each year (BOB for business-as-usual E10 production), the BR set BOBs show very similar or smaller GHG emissions.

The WTP GHG emissions of E set and BR set BOB gasolines produced in configuration refineries are also compared to that produced in PADD refineries. A given (E set or BR set) gasoline BOB's WTP GHG missions in PADD 3 refinery are between those of the LtCOK and HvyCOK refineries. This is an expected result, as a PADD 3 refinery is a conceptual aggregate refinery summing up all Regional facilities physically present nowadays, which are predominantly LtCOK and HvyCOK refineries. Comparing the WTP GHG emissions for E set gasoline BOBs in a CA refinery with those in a COKHCK refinery shows that emissions in the former are slightly higher, with the difference stemming from the feedstock stage (crude recovery). The GHG emissions at the fuel stage (refinery processing) are similar for the two refineries. This is consistent with the general observation that refinery facilities in CA are predominantly the COKHCK type.

The WTP GHG emissions for BR set BOB gasolines and E set BOB gasolines were compared for a PADD 3 refinery and for CRK, LtCOK, and HvyCOK refineries. In a PADD 3 refinery, with the same RON (97) and similar bio-blending levels, the BR2 BOB (to blend with 27 vol% BR) has higher WTP GHG emissions than the Fuel 15 BOB (to blend with 30% ethanol).

7.3 WTP Energy Use and GHG Emissions of Ethanol from Corn Starch and Corn Stover

The energy use associated with obtaining ethanol feedstock and producing ethanol from both corn starch and corn stover are shown in Figure 7-35 below. The results are from the default values of GREET 2016.

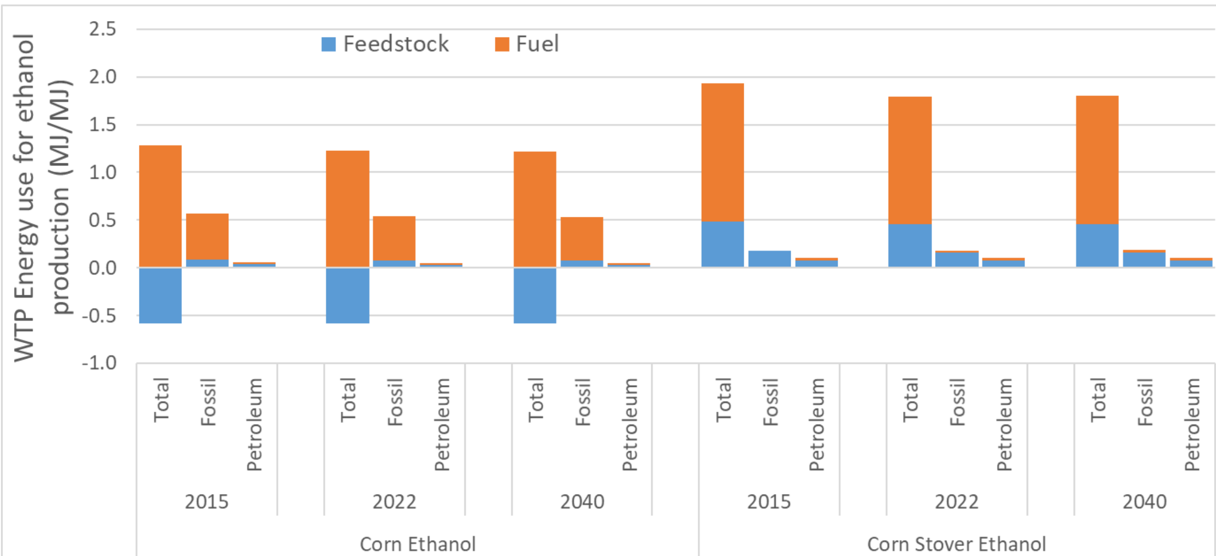


Figure 7-35. Energy Use of Ethanol Feedstock and Ethanol Production for Both Corn Starch and Corn Stover

It is worth noting that corn ethanol has large negative total energy use at the feedstock stage (obtaining corn starch), because of the large displacement credits corn starch ethanol receives. Corn starch ethanol production also produces a large quantity of co-product: “dry” mills produce distillers’ dried grain with soluble (DDGS), used for animal feed, and corn oil, while “wet” mills produce corn gluten feed (CGF), corn gluten meal (CGM) (both animal feeds) and corn oil.

For example, dry mills without corn oil extraction coproduce 5.63 lb. of DDGS per gallon of ethanol, while dry mills with corn oil extraction coproduce 5.36 lb. of DDGS and 0.19 lb. of corn oil per gallon of ethanol. Wet mills coproduce 1.22 lb. of CGM, 5.28 lb. of CGF and 0.98 lb. of corn oil per gallon of ethanol. These coproduced animal feeds are assumed to displace conventional animal feeds, including corn, soybean meal, urea and soy oil, and this displacement in turn creates renewable energy credits, shown as negative energy use in the graph in Figure 7-35.

Combining the energy use in the feedstock and fuel production stages results in the WTP energy use of ethanol, shown in Table 7-1.

Table 7-1. WTP Energy Use in Ethanol Production from Corn Starch and Corn Stover

	Corn Starch Ethanol			Corn Stover Ethanol		
Year	Total Energy (MJ/MJ)	Fossil (MJ/MJ)	Petroleum (MJ/MJ)	Total Energy (MJ/MJ)	Fossil (MJ/MJ)	Petroleum (MJ/MJ)
2015	0.61	0.57	0.05	1.93	0.16	0.11
2022	0.55	0.54	0.05	1.79	0.18	0.10
2040	0.54	0.53	0.05	1.80	0.19	0.10

When the energy use for WTP ethanol production from corn stover is compared to that of production from corn starch, the former consumes much more total energy, but much less fossil energy, than the latter. This indicates that while the ethanol production from corn stover is more energy intensive than that from corn starch, most energy consumed is from non-fossil sources, emitting biogenic CO_2 and not contributing to total fossil GHG emissions. For corn starch ethanol production, petroleum energy use is only about 10% of the total fossil energy use, the remainder being from natural gas and coal (mostly natural gas—coal use is estimated to be very limited at each production stage). Interestingly, corn stover ethanol production consumes more petroleum energy than corn starch ethanol production. This can partly be attributed to the use of diesel fuel during corn stover collection and transportation.

The GHG emissions of the two ethanol production pathways are shown in Figure 7-36.

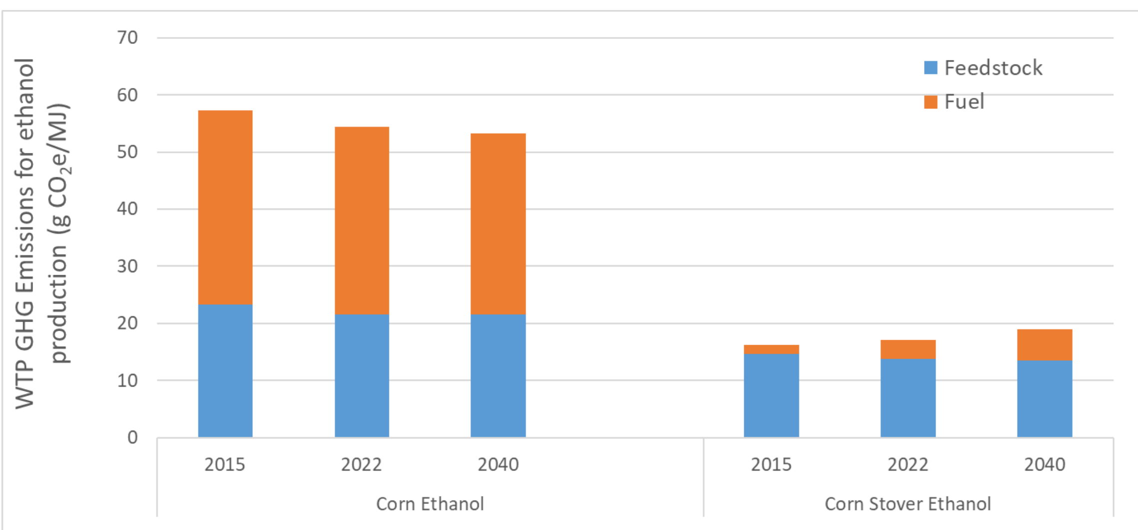


Figure 7-36. The WTP GHG Emissions Breakdown for Ethanol Production

Consistent with the fossil energy use trend, the GHG emissions for corn starch ethanol production are higher than those for corn stover ethanol. The difference is mostly caused by the process energy use during the fuel production process. The corn stover process uses biomass for energy supply and produces surplus electricity for export, which generates credit, while the corn starch process uses fossil energy for process heat requirements. In the corn stover to ethanol process, a large amount of biogenic CO_2 (90.8 g/MJ EtOH for 2015, 85.8 g/MJ EtOH for 2022 and 85.8 g/MJ EtOH for 2040) is generated but not counted in the net (fossil) GHG emissions. There is some GHG emission difference between corn starch ethanol and corn stover ethanol in the feedstock stage as well. As discussed in Section 4, the marginal allocation method between corn grain and corn stover attributes much less fertilizer and energy use to corn stover than to corn grain, resulting in lower GHG emissions associated with corn stover feedstock.

A comparison of the two pathways indicates that the energy use and GHG emissions of ethanol from corn stover and corn starch differ significantly, serving as two representative pathways (corn ethanol is incumbent and corn stover ethanol is cellulosic surrogate) to estimate GHG emissions for ethanol production.

7.4 WTP Energy Use and GHG Emissions of BR Stream Production with Different Hydrogen Sources

The production of the BR bioreformate blendstock requires a large hydrogen supply. The source of hydrogen supply can have significant impact on BR stream GHG emissions, as shown in Figure 7-37.

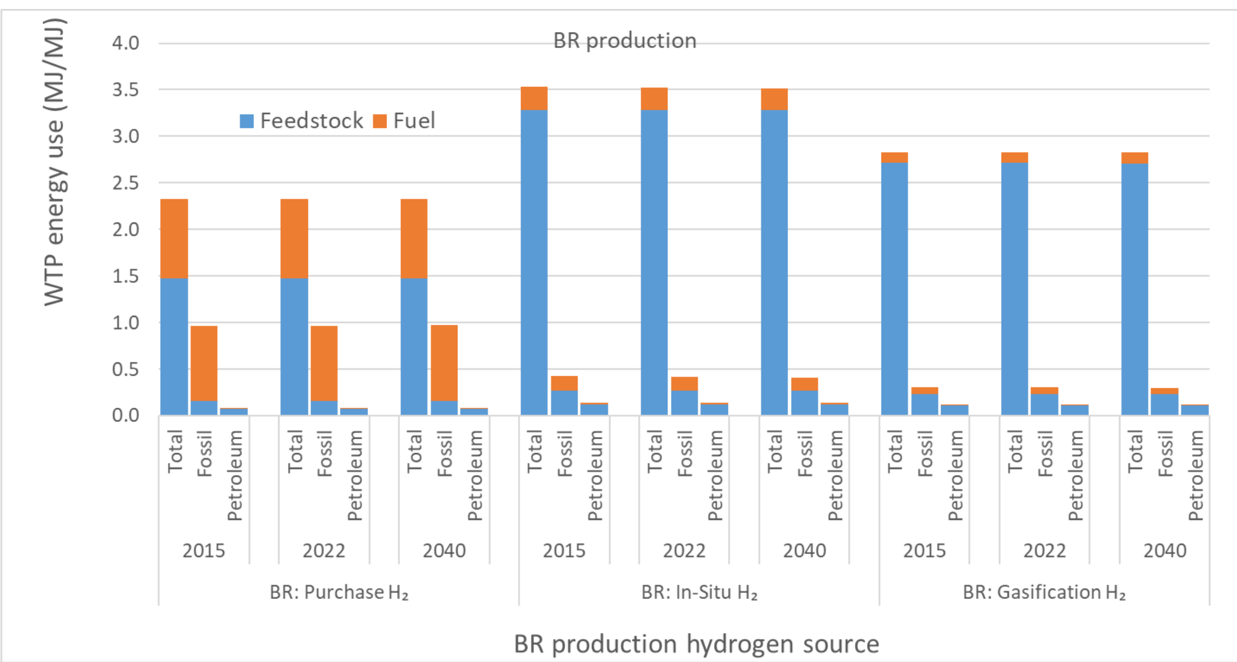


Figure 7-37. Energy Use for BR Stream Production with Three H_2 Sources

The comparison of BR production with different hydrogen sources show that all three pathways have significant energy use. With purchased hydrogen provided by industrial SMR, the BR production with purchased hydrogen pathway has the lowest WTP total energy use, the highest WTP fossil energy use, and the lowest petroleum energy use, as SMR consumes a significant amount of natural gas. On the other hand, with hydrogen produced from bio-intermediates, the in-situ hydrogen pathway has the highest total energy use but much lower fossil energy use, as the bio-intermediate is a renewable source. With hydrogen produced via woody chips gasification, the gasification hydrogen pathway shows the lowest fossil energy use but high total energy use.

To further examine energy use for BR production, total energy use is categorized as petroleum energy, natural gas/coal energy (NGC, difference of fossil energy and petroleum energy), and renewable energy (difference of total energy and fossil energy). See Figure 7-38.

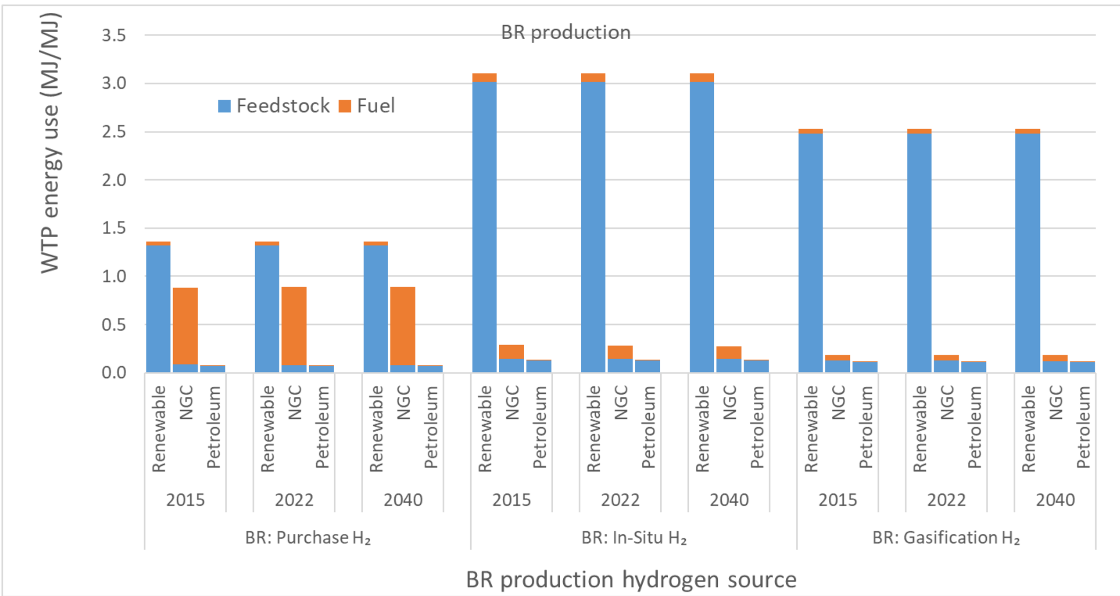


Figure 7-38. Energy Use (renewable, NGC and petroleum) for BR Stream Production with Three H_2 Sources

Comparing the energy sources, it is not surprising to observe that the purchased hydrogen option shows much higher natural gas/coal use at the fuel stage, due to the use of natural gas as a feedstock for hydrogen production via the SMR process.

The GHG emissions of the three H_2 technologies are shown in Figure 7-39.

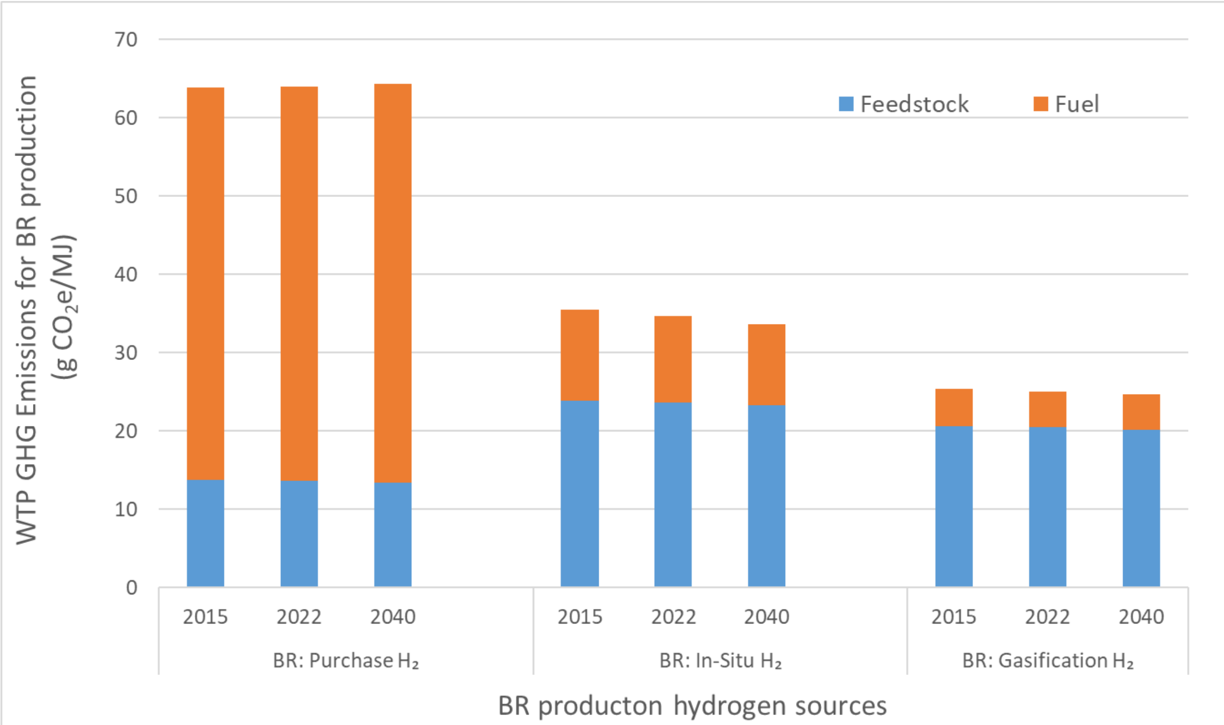


Figure 7-39. GHG Emissions for BR Blendstock Production with Three H_2 Sources

BR blendstock production with purchased hydrogen shows much higher GHG emissions than the other two pathways. Although it has lower GHG emissions in the biomass feedstock stage for BR stream production, it has significantly higher GHG emissions during the fuel stage for BR stream production, as the SMR plant is an energy-intensive unit with significant CO_2 from hydrogen production. The details of various hydrogen production processes are described and discussed in the report by Davis et al.[10].

8. Pump-To-Wheel Analysis for Bio-Blended High Octane Fuels

To calculate the WTW per-mile energy use and GHG emissions associated with the use of high-octane fuels in internal combustion engine vehicles, the per-mile energy use and GHG emissions during vehicle operation, or the PTW phase, must be quantified. This requires careful matching of fuel octane specifications with engine design parameters (e.g., compression ratio and piston displacement) to maximize engine performance specifications (e.g., efficiency and maximum power and torque outputs at desired engine speeds).

To evaluate the potential fuel economy gains of E set and BR set fuels, engine tests were conducted at Oak Ridge National Laboratory for both the U.S.DRIVE [4] and CRC AVFL-20 [9] studies. The engine tests results were further analyzed and modeled by ORNL in the Autonomie vehicle system simulation tool to obtain "window sticker" fuel economy results for vehicles. The details of engine tests and vehicles fuel economy research are documented in a separate ORNL report by Sluder et al. [4]. Some results are shown below as key input information for the PTW analysis in the present report.

Fuels included in the WTW study are regular E10 gasoline fuel with RON of 91, as well as high-octane fuel blends at two RON levels (RON ~ 97 and RON ~ 101) containing 20% or 30% ethanol by volume (E20 or E30), and three fuel blends with 9% and 27% by volume high-octane bioreformate surrogates (BRS) in the blend (RON ~ 97 or ~ 101). The measured or tested properties of these fuels are shown in Table 8-1. Fuels F1, F7, F10, F14, F15, F16, and F19 were designed, characterized, and engine tested in CRC's AVFL-20 project [9]. Fuels F18, F20, BR1, BR2, and BR4 were designed for this U.S.DRIVE project and were tested at ORNL in the same engine used for the CRC project and vehicle modeling conducted using the same procedures.

Table 8-1. Matrix of Fuels Produced for the U.S.DRIVE and CRC Engine Test Studies and Their Properties

Fuel ID	RON	EtOH or BR Content (Vol%)	Heating Value (Btu/gallon)	Renewable Energy %	Fuel Carbon Content (mg/Btu)	Biogenic % of Carbon Content
Baseline[1]	91	10	111,986	6.9%	76.4	6.8%
F1[2]	91	10	110,840	7.1%	75.6	7.1%
F7[2]	100.1	10.1	108,373	7.1%	73.9	7.2%
F10[2]	91	10	113,131	6.7%	77.1	6.5%
F14[2]	96.6	10.4	112,486	7.0%	76.6	6.9%
F15[2]	96.5	30.4	103,097	22.4%	76.5	22.0%
F16[2]	101.1	10.2	112,572	6.9%	76.8	6.7%
F18	101	20	108,358	14.1%	77.0	13.8%
F19[2]	101	29.9	101,966	22.6%	75.6	22.5%
F20	97.3	20	108,736	14.1%	77.0	13.7%
BR1	97.6	9	116,602	9.9%	77.7	10.9%
BR2	97.3	27	116,652	29.7%	78.1	32.5%
BR4	101.6	27	118,278	29.3%	78.6	31.9%

[1] Average of fuels F1 and F10
[2] CRC AVFL-20 Project [9]
Note: The properties and engine test results of WG gasoline are not shown here as the WTW analysis cannot be carried out due to the infeasibility of LP modeling for the WG set fuels.

Detailed hydrocarbon analyses for all the fuels were provided by ORNL and the results were used to verify the ethanol content (by direct ethanol content measurement) and bioreformate content (through measured increase in bioreformate surrogate marker compounds) of the fuels. This examination confirmed that the finished fuels contained approximately the targeted amount of the ethanol and biorefomrate shown in Table 8-1

The CRC AVFL-20 and the U.S.DRIVE fuels were tested at ORNL in a Ford 1.6 L turbocharged, direct injection EcoBoost production engine at one or two compression ratios by using different pistons: the base production ratio of 10.5:1 and a higher ratio of 11.4:1 [4]. Fuels F1 and F10 are 91 RON E10 fuels, having low and high octane sensitivities, respectively. **The average vehicle performance of these two fuels (F1 and F10) was adopted as the baseline fuel-vehicle combination for comparison with other high-octane fuel-vehicle systems**[10]. The second group of fuels in Table 8.1 (F7 and F14-F20) are E set fuels, high-octane fuels with various ethanol blending levels and octane ratings. The last three fuels in Table 8.1 are BR set fuels, blends of petroleum-based reformate, serving as surrogate for high-octane bioreformate compositions, which consist mainly of aromatic hydrocarbons.

In the engine testing and vehicle simulation portion of this U.S.DRIVE study [4], three ON/CR values of 5.6, 3.7, and 3.0 were used in combination with the measured RON values in Table 8.1 to estimate the average fuel economies for new 2015 model year (MY) vehicles (using small SUV as representative of fleet) enabled by each fuel, shown in Table 8-2, using the method in Leone et al. [8].

Table 8-2. Projected On-Road Adjusted Vehicle Fuel Economy for Model Year 2015 Based on the USCAR Method

				Average New Vehicle On-Road Fuel Economy, MPG_{E10}			
Fuel	RON	Heating Value (BTU/gal)	EtOH/BR Content (Vol%)	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR
Base	91	111,986	10	27.4	--	--	--
F1	91	110,840	10	27.5	--	--	--
F7	100.1	108,373	10.1	--	28.7	28.5	28.2
F10	91	113,131	10	27.2	--	--	--
F14	96.6	112,486	10.4	--	28.3	28.1	27.9
F15	96.5	103,097	30.4	--	28.6	28.4	28.2
F16	101.1	112,572	10.2	--	28.8	28.6	28.3
F18	101	108,358	20	--	29.0	28.8	28.4
F19	101	101,966	29.9	--	29.1	28.9	28.6
F20	97.3	108,736	20	--	28.5	28.4	28.1
BR1	97.6	116,602	9	--	28.3	28.1	27.8
BR2	97.3	116,652	27	--	28.2	28.1	27.8
BR4	101.6	118,278	27	--	28.7	28.5	28.2

These fuel economy gains can be applied to the fuel consumption of 2015baseline vehicles to estimate the fuel consumption of corresponding model year vehicles using high-octane fuels (97 and 101 RON) and higher CR [4]. Note that these projections are for new vehicles and are not the on-road fleet average for those years.

[10] LP modeling produced different baseline E10 gasolines varying with refinery configuration and year, but their fuel economies were assumed to be the same for all refinery products, and only vary with year with fuel economy gain.

Projected on-road energy use (BTU/mile) and CO_2 emissions (per mile basis) for 2015 vehicles using baseline and high-octane fuels are summarized in Tables 8-3 and Table 8-4. The contribution of renewable fuels and biogenic carbon to the on-road energy use and CO_2 emissions is itemized.

Table 8-3. Projected Model Year 2015 New Vehicle Energy Use for Using Baseline and High-Octane Fuels

	2015 Petroleum Energy (Btu/mile)				2015 Bio-energy (Btu/mile)			
	On-Road Energy Use				On-Road Energy Use			
Fuel	CR10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR
Base	3,807	--	--	--	282	--	--	--
F1	3,779	--	--	--	289	--	--	--
F7	--	3,621	3,647	3,689	--	277	279	282
F10	3,835	--	--	--	275	--	--	--
F14	--	3,681	3,704	3,734	--	277	279	281
F15	--	3,040	3,060	3,085	--	878	883	890
F16	--	3,617	3,642	3,686	--	268	270	273
F18	--	3,320	3,343	3,384	--	545	549	555
F19	--	2,975	2,996	3,033	--	869	875	886
F20	--	3,370	3,393	3,424	--	553	557	562
BR1	--	3,568	3,592	3,625	--	392	395	398
BR2	--	2,788	2,806	2,831	--	1178	1186	1196
BR4	--	2,758	2,777	2,810	--	1143	1151	1165

Source: Sluder et al. [4].

Table 8-4. Projected Model Year 2015 New Vehicle GHG Emissions Using Baseline and High-Octane Fuels

	2015 Fossil CO_2 (g/mile)				2015 Biogenic CO_2 (g/mile)			
Fuel	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR
Base	291.0	--	--	--	21.3	--	--	--
F1	285.7	--	--	--	21.8	--	--	--
F7	--	267.4	269.3	272.4		20.7	20.9	21.1
F10	296.3	--	--	--	20.7	--	--	--
F14	--	282.4	284.1	286.4	--	20.9	21.1	21.2
F15	--	233.8	235.3	237.2	--	65.9	66.4	66.9
F16	--	278.3	280.3	283.6	--	20.0	20.1	20.4
F18	--	256.4	258.2	261.3	--	41.0	41.3	41.8
F19	--	225.3	226.9	229.7	--	65.4	65.9	66.7
F20	--	260.8	262.5	264.9	--	41.4	41.7	42.1
BR1	--	274.0	275.8	278.4	--	33.5	33.7	34.1
BR2	--	209.1	210.5	212.4	--	100.7	101.3	102.2
BR4	--	208.7	210.1	212.7	--	97.8	98.4	99.6

To estimate the corresponding baseline new vehicle fuel economies for model years 2022 and 2040, the projected fuel economy growth rate through 2040 reported in EIA's *Annual Energy Outlook 2018* (AEO 2018) was used [54]. The values for new vehicles are essentially the CAFÉ requirements for each year. AEO2018 projects an accelerated fuel economy improvement through 2025 and then a decelerated improvement through 2040. Based on the AEO 2018 projected fuel economy growth, we assumed a 20% gain in new vehicle fuel economy in 2022 and a 22.4% gain in 2040 (over 2015 new vehicle fuel economy). For example, the baseline new vehicle fuel consumption for model year 2015 is 3807+282=4089 Btu/mile. Thus, the baseline vehicle fuel consumption for model years 2022 and 2040 is estimated at 4089/(1+20%)=3408 Btu/mile and 4089/(1+22.4%)=3341 Btu/mi, respectively. The results are shown in Table 8-5 to Table 8-8.

Table 8-5. MY 2022 New Vehicle Energy Consumption Using Baseline and High-Octane Fuels

	2022 Petroleum Energy (Btu/mile)				2022 Bio-energy (Btu/mile)			
	On-Road Energy Use				On-Road Energy Use			
Fuel	CR10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR
Base	3,173	--	--	--	235	--	--	--
F1	3,149	--	--	--	241	--	--	--
F7	--	3,018	3,039	3,074	--	231	232	235
F10	3,196	--	--	--	229	--	--	--
F14	--	3,068	3,087	3,112	--	231	232	234
F15	--	2,534	2,550	2,571	--	731	736	742
F16	--	3,014	3,035	3,071	--	223	225	228
F18	--	2,767	2,786	2,820	--	454	457	463
F19	--	2,479	2,497	2,527	--	724	729	738
F20	--	2,809	2,827	2,853	--	461	464	468
BR1	--	2,973	2,993	3,021	--	327	329	332
BR2	--	2,323	2,338	2,359	--	982	988	997
BR4	--	2,298	2,314	2,342	--	953	959	971

Table 8-6. MY 2022 New Vehicle GHG Emissions Using Baseline and High-Octane Fuels

	2022 Fossil CO_2 (g/mile)				2022 Biogenic CO_2 (g/mile)			
Fuel	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR
Base	242.5	--	--	--	17.7	--	--	--
F1	238.1	--	--	--	18.2	--	--	--
F7	--	222.8	224.4	227.0		17.3	17.4	17.6
F10	246.9	--	--	--	17.3	--	--	--
F14	--	235.3	236.8	238.7	--	17.4	17.5	17.7
F15	--	194.8	196.1	197.7	--	55.0	55.3	55.8
F16	--	231.9	233.6	236.4	--	16.7	16.8	17.0
F18	--	213.7	215.2	217.8	--	34.2	34.4	34.9
F19	--	187.8	189.1	191.4	--	54.5	54.9	55.6
F20	--	217.3	218.7	220.7	--	34.5	34.7	35.0
BR1	--	228.4	229.9	232.0	--	27.9	28.1	28.4
BR2	--	174.3	175.4	177.0	--	83.9	84.5	85.2
BR4	--	173.9	175.1	177.2	--	81.5	82.0	83.0

Table 8-7. MY 2040 New Vehicle Energy Consumption Using Baseline and High-Octane Fuels

	2040 Petroleum Energy (Btu/mile)				2040 Bio-energy (Btu/mile)			
	On-Road Energy Use				On-Road Energy Use			
Fuel	CR10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR
Base	3,110	--	--	--	231	--	--	--
F1	3,088	--	--	--	236	--	--	--
F7	--	2,958	2,979	3,014	--	226	228	230
F10	3,133	--	--	--	225	--	--	--
F14	--	3,007	3,026	3,051	--	226	228	230
F15	--	2,484	2,500	2,520	--	717	722	727
F16	--	2,955	2,975	3,011	--	219	221	223
F18	--	2,712	2,732	2,765	--	445	448	454
F19	--	2,431	2,448	2,478	--	710	715	724
F20	--	2,754	2,772	2,797	--	452	455	459
BR1	--	2,915	2,934	2,962	--	320	322	325
BR2	--	2,278	2,293	2,313	--	962	969	977
BR4	--	2,253	2,269	2,296	--	934	940	952

Table 8-8. MY 2040 New Vehicle GHG Emissions Using Baseline and High-Octane Fuels

	2040 Fossil CO_2 (g/mile)				2040 Biogenic CO_2 (g/mile)			
Fuel	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR
Base	237.7	--	--	--	17.4	--	--	--
F1	233.7	--	--	--	17.8	--	--	--
F7	--	218.4	220.0	222.5		--	--	--
F10	241.8	--	--	--	16.9	--	--	--
F14	--	230.7	232.1	234.0	--	17.1	17.2	17.3
F15	--	191.0	192.2	193.8	--	53.9	54.2	54.7
F16	--	227.4	229.0	231.7	--	16.3	16.4	16.6
F18	--	209.5	210.9	213.5	--	33.5	33.8	34.2
F19	--	184.1	185.4	187.7	--	53.5	53.8	54.5
F20	--	213.0	214.5	216.4	--	33.8	34.0	34.4
BR1	--	223.9	225.4	227.5	--	27.4	27.6	27.8
BR2	--	170.9	172.0	173.5	--	82.3	82.8	83.5
BR4	--	170.5	171.7	173.8	--	79.9	80.4	81.4

For all years and all ON/CR ratios, the fossil CO_2 emissions (g/mile) are lower for the BR set fuels than the ethanol based fuels (E-set) at similar bio-contents. For example, at ON/CR=3.0 in 2015, the BR2 and BR4 fuels containing 27 vol.% bioreformate have about 209 g/mile fossil fuel CO_2 emissions while the F15 and F19 fuels containing 30 vol.% ethanol have 225–233 g/mile fossil fuel CO_2 emissions.

The vehicle GHG emissions per MJ basis (PTW GHG emissions per MJ) is calculated from fossil GHG (g/mile) divided by total energy (Btu/mile). The total energy (Btu/mile) is the sum of fossil energy (Btu/mile) and bio- energy (Btu/mile). For example, for the high RON fuel F18 in 2022, in Table 8-5, with the assumption of 3.0 ON/CR, the total energy use (Btu/mile)=2,767+454 =3,221 (Btu/mile). In Table 8-6, F18 with assumption of 3.0 ON/CR, the fossil GHG emissions are 214 g/mile. Thus, the (fossil) GHG emission per energy basis = 214/3221 = 0.0665 (g/Btu). Converting 0.0665 (g/Btu)* 1,000,000 (Btu to mmBtu)/1055 (mmBtu to MJ), results in 62.9 g/MJ. The energy uses are calculated similarly. It is worth mentioning that all the fossil energy used for vehicle is regarded as petroleum energy.

The vehicle GHG emissions (PTW GHG emissions) results for E set fuels and BR set fuels are shown in Table 8-9. It is worth noting that the vehicle PTW emission per MJ does not vary with fuel economy derived from various ON/CR assumptions, as it only describes how much fossil content is embedded in the finished gasoline.

Table 8-9. New Vehicle GHG Emissions and Energy Uses via Using Baseline Fuel and High-Octane Fuels per MJ Total Energy basis, for all years

Fuel	RON	EtOH/BR Content (Vol%)	Vehicle (PTW) emissions (g/MJ)	Total energy	Fossil energy	Petroleum energy
Base	91	10	67.4	1.00	0.93	0.93
F1	91	10	66.6	1.00	0.93	0.93
F7	100.1	10.1	65.0	1.00	0.93	0.93
F10	91	10	68.3	1.00	0.93	0.93
F14	96.6	10.4	67.6	1.00	0.93	0.93
F15	96.5	30.4	56.6	1.00	0.78	0.78
F16	101.1	10.2	67.9	1.00	0.93	0.93
F18	101	20	62.9	1.00	0.86	0.86
F19	101	29.9	55.6	1.00	0.77	0.77
F20	97.3	20	63.0	1.00	0.86	0.86
BR1	97.6	9	65.6	1.00	0.90	0.90
BR2	97.3	27	50.0	1.00	0.70	0.70
BR4	101.6	27	50.7	1.00	0.71	0.71

The vehicle GHG emissions, or PTW results are then combined with the WTP results of gasoline BOB, and that of ethanol and bioreformate from the previous sections to calculate the finished gasolines WTW energy uses and GHG emissions, per MJ basis and per mile basis, which are presented in Section 9.

9. WTW Energy and GHG Analysis for Bio-Blended High Octane Fuels

In the WTP segment of the total WTW emissions of GHG, production of some of the BOBs for high-octane gasoline show higher GHG emissions than their baselines (BAU production). However, the higher GHG emissions during WTP stage can be offset by GHG reductions due to bio-content presence in gasolines (lowing fossil carbon content upon combustion, per MJ basis) and the fuel economy gains enabled by the high-octane feature (per-mile basis).

9.1 WTW Energy and GHG Results of E Set Fuels

Combining the energy use and GHG emissions for WTP gasoline BOB and ethanol/BR production with the PTW of finished gasoline gives the WTW results of bio-blended high-octane fuels.

9.1.1 WTW Analysis of Aggregate Refineries Base Cases

9.1.1.1 Aggregate Base Cases WTW Energy Use and GHG Emissions per MJ of Finished Fuels

Adding the aggregate base case WTP BOB results in Section 7 to the ethanol production results and base case E10 PTW results in Section 8 gives us the WTW results for aggregate refinery base cases. The former two vary with PADD refinery, year and ethanol source, and are combined to become the WTP results of finished gasolines. The latter is constant per MJ but varied by year on a per-mile basis.

The base case WTW results are shown in Figure 9-1 below, broken down by WTP and PTW stage of finished gasolines. The data are also listed in Appendix 4 in Table A4-1.

There is a noticeable difference (6%–7%) in WTW total energy use between corn stover E10 and corn starch E10, with corn stover E10 consuming more total energy. However, WTP total energy of corn stover ethanol production contains more bio-energy, resulting in less use of fossil energy than corn starch ethanol, leading to lower net GHG emissions (g CO_2e/MJ). In addition to petroleum energy, fossil energy includes energy from natural gas and coal. Although petroleum is the major fossil energy resource for E10 gasoline production and use, non-petroleum energy, mostly natural gas, also contributes significantly to WTW E10 fossil energy use. The non-petroleum/petroleum ratio is especially high for PADD 2, due to the use of energy-intensive oil sands there.

The base case E10 GHG emissions, with ethanol from corn starch and corn stover, are shown in Figure 9-2. The WTP values of finished gasolines are calculated by adding up gasoline BOB WTP values and ethanol WTP values based on their energy shares, shown in Section 7. For example, for PADD 2 in 2015, the gasoline BOB WTP GHG is 28.1 g/MJ BOB, and corn starch ethanol WTP GHG is 57 g/MJ ethanol, the energy share of gasoline BOB and ethanol are 93.1% and 6.9%, respectively. Then the WTP GHG of finished gasoline is 28.1 (g CO_2e/MJ BOB) × 97.1% (MJ BOB/MJ finished gasoline) + 57 (g CO_2e /MJ ethanol) * 6.9% (MJ ethanol/MJ finished gasoline) =30.1 (gCO_2e /MJ finished gasoline).

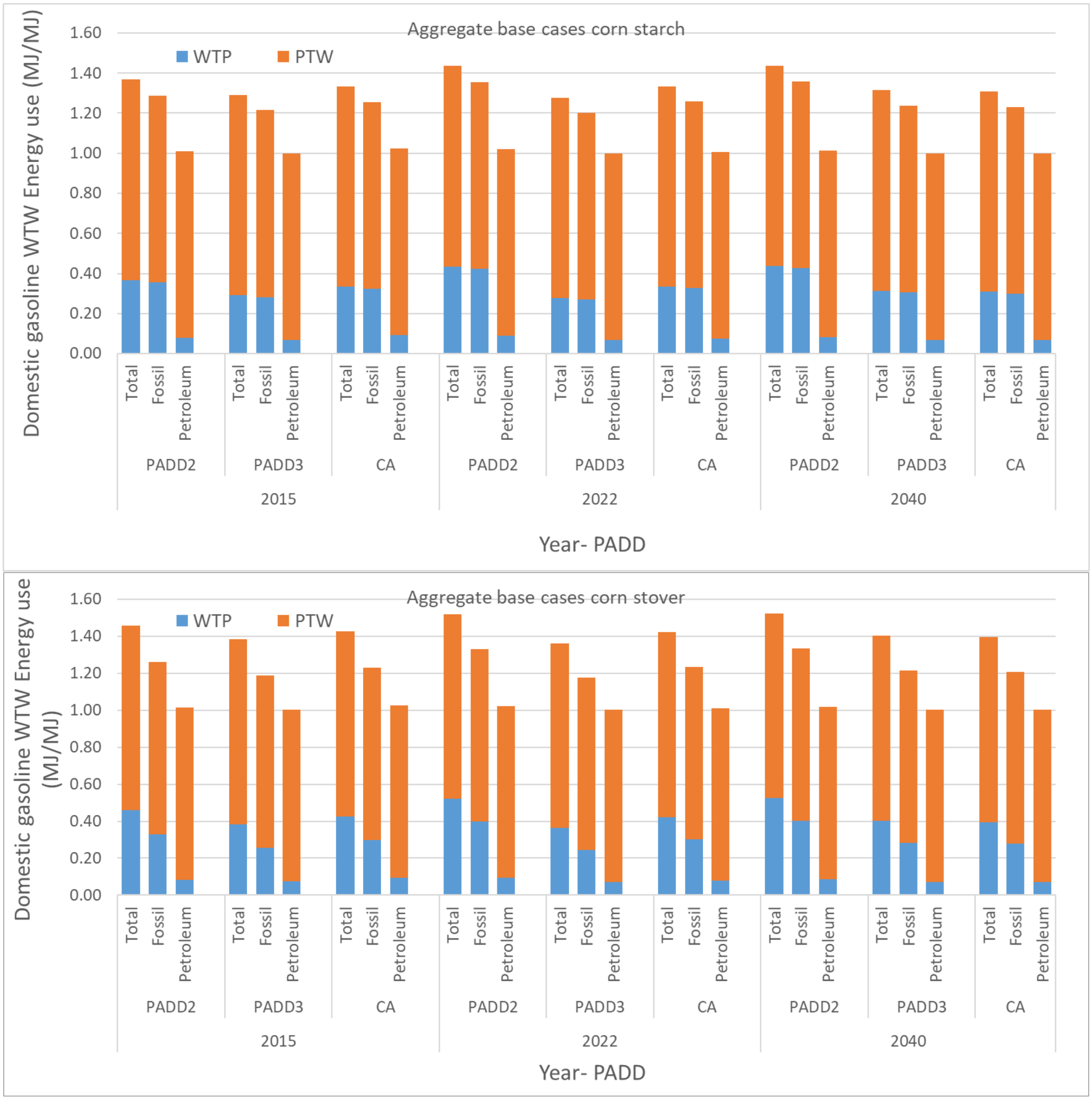


Figure 9-1. WTW Energy Use of PADD Base Case E10 (Finished) Gasoline in Three Years with Ethanol from Corn Starch and Corn Stover, Respectively.

The PTW values are calculated for each case by taking the corresponding base gasoline fossil CO_2 GHG Emission values in Tables 8-4, 8-6, and 8-8 (g/mile), dividing by the corresponding sum of the petroleum and bio-energy on-road energy use values in Tables 8-3, 8-5, and 8-7 (Btu/mile), multiplying by $1x10^6$ Btu/MM Btu, and dividing by 1,055 MJ/MM Btu. For example, for PADD 2 in 2015, the calculation is: (291g CO_2e /mile)/(3807+282)(Btu/mile)*($1x10^6$ Btu/MM Btu)/(1,055 MJ/1 MM Btu)=67.4 g CO_2e /MJ.

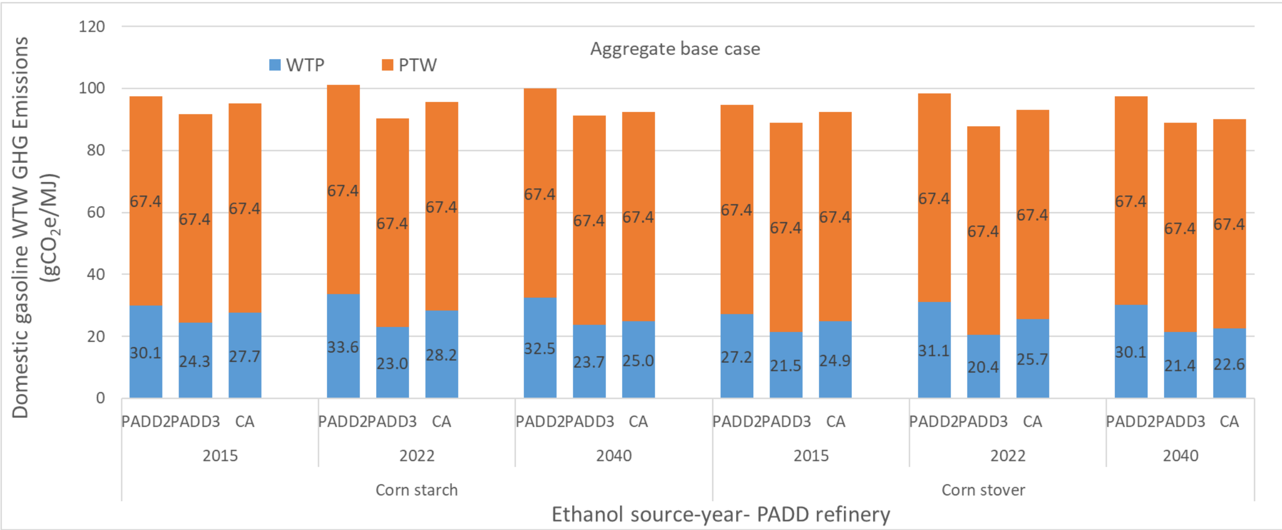


Figure 9-2. WTW GHG Emissions of PADD Base Cases E10 Fuels (Domestic Finished Gasolines)

As expected, base case E10 gasolines with corn starch ethanol have GHG emissions (about 2–3 g/MJ higher) higher than gasolines with corn stover ethanol. For each year studied, E10 gasoline in PADD 2 refineries has the highest WTW GHG emissions because of its higher emissions at the WTP stage, due to oil sands use. For PADD 2 base cases, baseline GHG emissions increase from 2015 to 2022 and decrease slightly from 2022 to 2040. For PADD 3 cases, baseline GHG emissions decrease slightly from 2015 to 2022, then increase slightly from 2022 to 2040. For CA cases, GHG emissions increase then decreases for the studied periods. The change trends of these base case gasoline GHG emissions are a result of the changes in crude slate and in refinery product slates, and responsive refinery operation changes.

9.1.1.2 Aggregate Base Case WTW Energy Use and GHG Emissions Per Mile Driven

WTW energy use for aggregate base case domestic gasolines (without accounting for the export gasoline) were further calculated for per mile driven based on the energy uses (depending on fuel economies) listed in Section 8. The gasoline WTP energy uses are calculated by summing up the WTP energy uses of gasoline BOB and ethanol in Section 7. The total PTW values are calculated by summing the petroleum and bio-energy on-road energy use (Btu/mile) values in Tables 8-3, 8-5, and 8-7 and multiplying by the conversion factor (1,055 MJ/1x10^6 Btu).

With a 20% fuel economy gain from 2015 to 2022 model-year (MY) cars, and another 12% gain from 2022 to 2040 MY cars, the changes in energy use on a per-mile basis are much more pronounced than the changes per MJ basis across the studied years. See Figure 9-3.

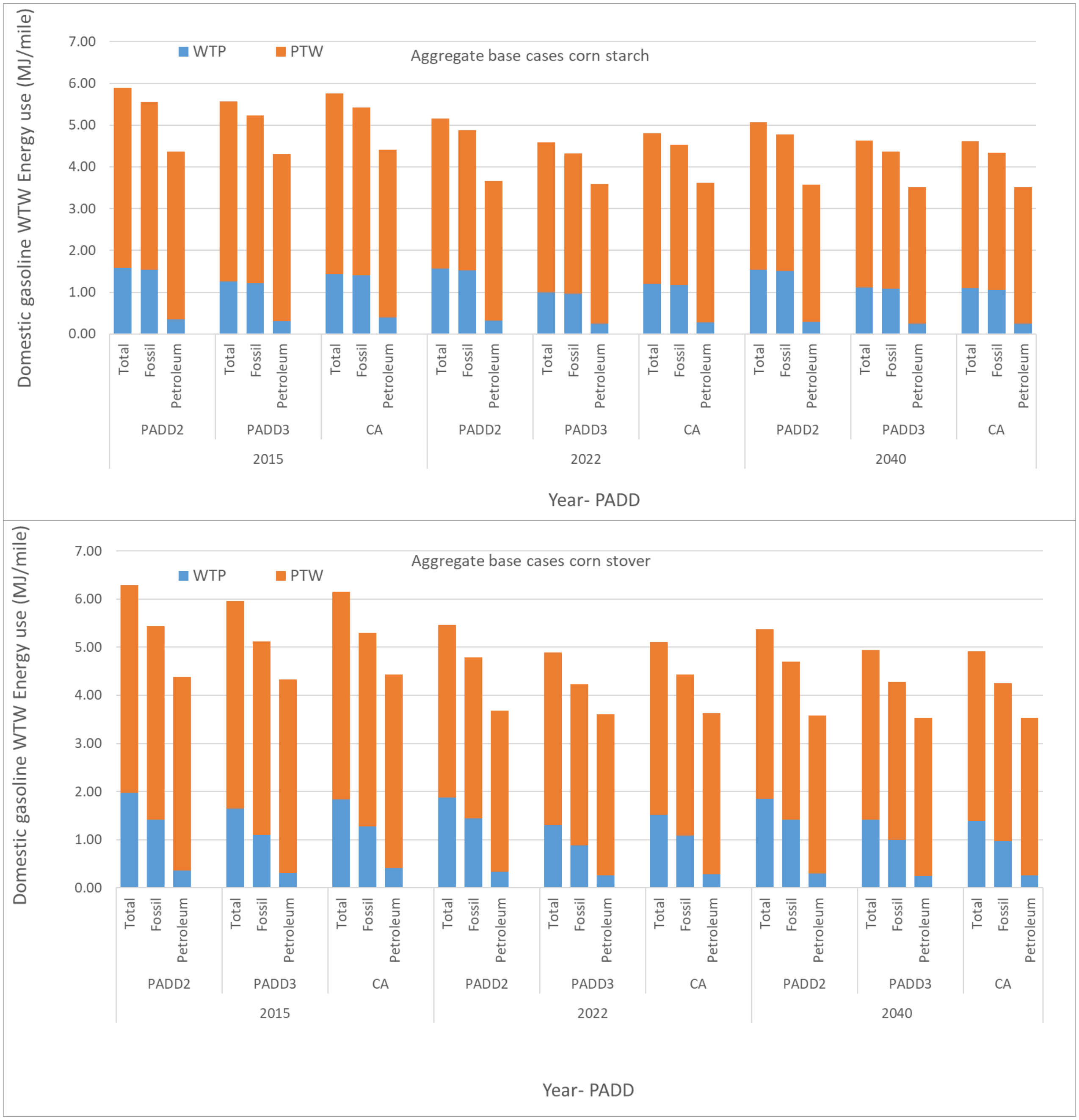


Figure 9-3. WTW Energy Uses of Aggregate Base Case Domestic (Finished) Gasolines Per Mile Driven with Corn Starch Ethanol and Corn Stover Ethanol, Respectively.

Similarly, when the fuel economy increase from 2015 through 2040 MYs is included, the differences in GHG emissions among gasolines of different PADD base cases on a per-mile basis are more pronounced than the differences on a per-MJ basis (see Figure 9-4). The WTP GHG emissions per mile values are converted from the energy uses per MJ fuel consumed by using fuel economy (mile/gallon) and fuel heating values. For example, for PADD 2 base gasoline in 2015 with corn starch ethanol, the WTP GHG emissions is 30.1 g CO_2e/MJ gasoline. The total energy on the per-mile basis is 30.1 (g CO_2e /MJ) /[(27.4 miles/gallon)/111,986 mmBtu/gallon/1,055.055 (MJ/mmBtu)]=129.6 g

CO_2e/mile. The PTW values come from the fossil CO_2 emission values in Tables 8-4, 8-6, and 8-8 for the base gasolines. With the sizeable fuel economy gain, all gasolines from different PADDs have their lowest GHG emissions in 2040.

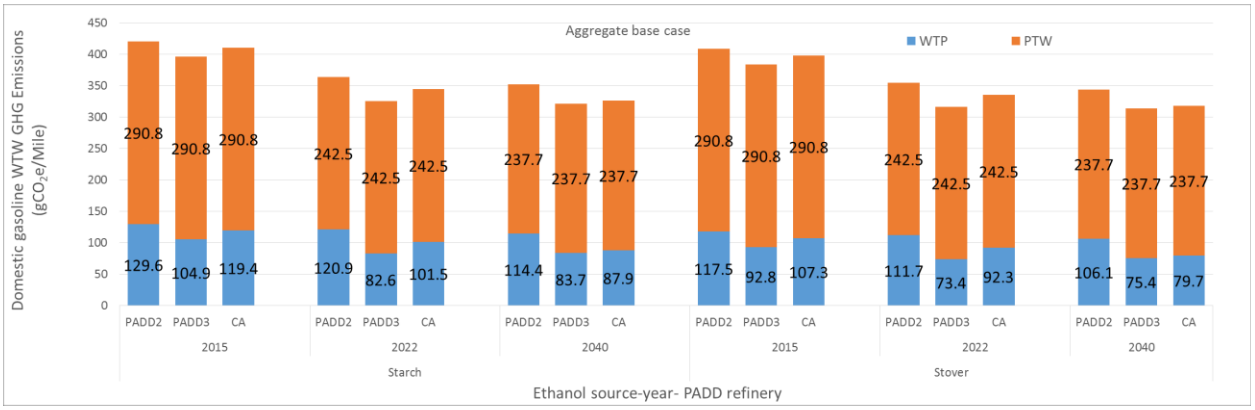


Figure 9-4. WTW GHG Emissions of Aggregate Base Case Domestic Finished Gasolines Per Mile Driven with Corn Starch Ethanol and Corn Stover Ethanol, Respectively.

9.1.2 WTW Results of Aggregate PADD Refineries with E Set Fuels Production

For E set fuels (domestic finished gasoline) produced in PADD refineries, combining the WTP results (adding WTP gasoline BOB results to ethanol production results) with the PTW results yields the WTW results. Again, for each E set fuel, the WTP results vary with PADD, year, and bio-blend source (corn starch and corn stover), while the PTW results hold constant for a given fuel property in a given year. Note that the projected PTW values are based on the values generated in Chapter 8 for the most optimistic ratio of 3.0 RON required per engine compression ratio increase. The results with 3.7 ON/CR and 5.6 ON/CR are presented in Appendix 4.

9.1.2.1 Aggregate Refinery E Set Fuels WTW Energy Use Per MJ of Fuel Used

Energy use (total energy, fossil energy and petroleum energy) along the E set fuels' WTW life cycles was calculated for ethanol from both corn starch and corn stover. For each E set fuel, the energy use of BAU and HOF gasolines varies with their different components (see Section 5), as shown in Table 9-1 and Figure 9-5.

Table 9-1. WTW Energy Use of E Set BAU and HOF Finished Gasolines in PADD 3 in 2022 with Ethanol from Corn Starch

Gasoline	BAU (MJ/MJ)			HOF (MJ/MJ)		
Fuel	Total	Fossil	Petroleum	Total	Fossil	Petroleum
2022 PADD 3 Corn Starch Ethanol						
F1	1.28	1.20	1.00	--	--	--
F7	1.29	1.23	1.00	1.25	1.19	1.01
F10	1.29	1.24	1.00	1.26	1.20	1.03
F14	1.27	1.21	1.00	1.27	1.21	1.02
F15	1.28	1.23	1.00	1.26	1.20	1.02
F16	1.29	1.23	1.00	1.26	1.09	0.88
F18	1.28	1.22	1.02	1.25	1.20	1.03
F19	1.27	1.22	1.00	1.30	1.15	0.94
F20	1.29	1.23	1.00	1.29	1.12	0.90
2022 CA Corn Starch Ethanol						
Gasoline	BAU (MJ/MJ)			HOF (MJ/MJ)		
Fuel	Total	Fossil	Petroleum	Total	Fossil	Petroleum
F1	1.36	1.18	1.00	--	--	--
F7	1.37	1.21	1.01	1.33	1.17	1.02
F10	1.38	1.21	1.01	1.34	1.17	1.04
F14	1.35	1.19	1.00	1.35	1.18	1.02
F15	1.37	1.20	1.00	1.34	1.17	1.03
F18	1.37	1.21	1.00	1.54	1.01	0.89
F19	1.36	1.20	1.02	1.34	1.17	1.04
F20	1.36	1.19	1.00	1.47	1.10	0.94

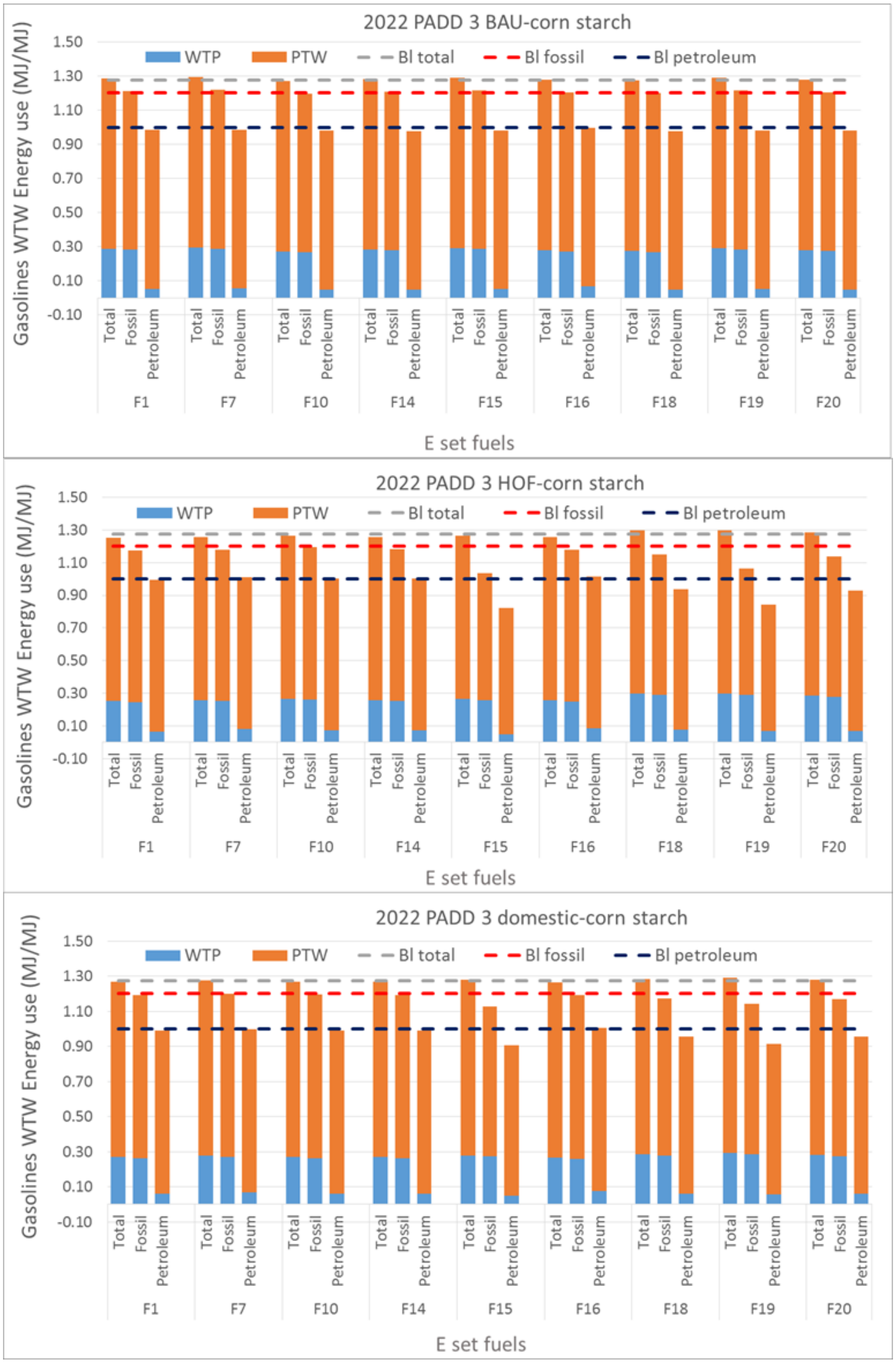


Figure 9-5. WTW Energy Uses for E set BAU, HOF and Domestic Finished Gasolines in PADD 3 in 2022 with Corn Starch Ethanol. Baseline (Bl) Uses Corn Starch Ethanol.

The results in Figure 9-5 are also listed in Appendix 4 Table A4-2 (corn starch ethanol) for details. The energy use (total, fossil, petroleum) for various E set BAU gasolines with ethanol from corn starch are similar to baselines. This is not surprising as BAU gasoline shares all the same specifications/constraints with base case E10 fuels, resulting in similar energy uses. For HOF gasoline with various bio-ethanol blending contents, the energy use relative to baseline differs for each fuel. Fossil energy use for HOF gasolines F15, F18, F19 and F20 is lower than baselines even though their WTP fossil energy use is higher than baseline. This is because their PTW fossil energy use is much lower than baseline, owing to their high level of ethanol blending, which dilutes the fossil energy on a per-MJ basis. Similarly, HOF gasolines F15, F18, F19 and F20 have much lower petroleum energy use due to the lower petroleum energy presence in the PTW stage.

Combining the WTW energy use of BAU gasoline and HOF gasoline yields the WTW energy use of the E set domestic gasoline. As expected, the energy use (total, fossil, and petroleum) of domestic (finished) gasolines F1, F7, F10, F14 and F16 (E10 fuels) is similar to baselines, and the domestic (finished) gasolines F15, F18, F19 and F20 (E20 and E30 fuels) show energy use (fossil and petroleum) lower than baselines.

As noted, for 2022 cases, the baseline is defined as E10 gasoline with corn starch ethanol. Among the E set fuels with corn stover ethanol in PADD 3, BAU gasolines have higher total energy use, but similar fossil and petroleum energy use to baseline. All of the E set HOF gasoline fuels show higher total energy use than baseline, especially the E20 and E30 gasolines F15, F18, F19, and F20. However, they show lower fossil energy and petroleum energy use, especially for E20 and E30 HOF gasolines F15, F18, F19 and F20. This is because production of corn stover ethanol relies more on bio-energy (contributing to total energy use), and less on fossil energy and petroleum energy, compared with corn starch ethanol. See Figure 9-6. The data in Figure 9-6 are also listed in Appendix 4 Table A4-3 (corn stover ethanol) for details.

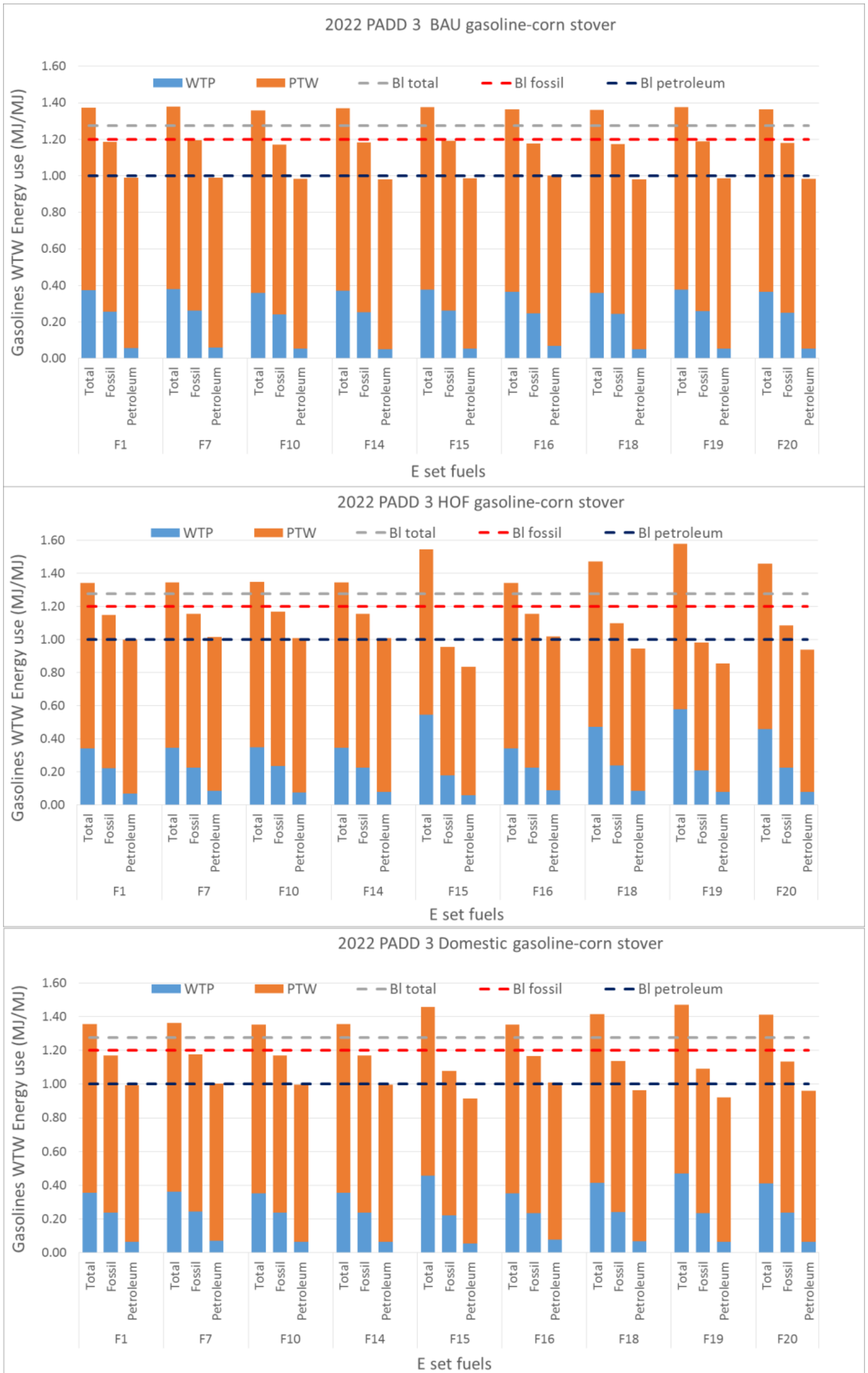


Figure 9-6. WTW Energy Use of E Set BAU, HOF and Domestic Finished Gasolines in PADD 3 in 2022 with Corn Stover Ethanol. Baseline (Bl) Uses Corn Starch Ethanol.

For E set domestic gasolines produced in PADD 3 in 2022, energy use with the two ethanol sources can also be compared by tracking energy use in petroleum energy, natural gas-coal energy (NGC), and renewable energy. See Figure 9-7.

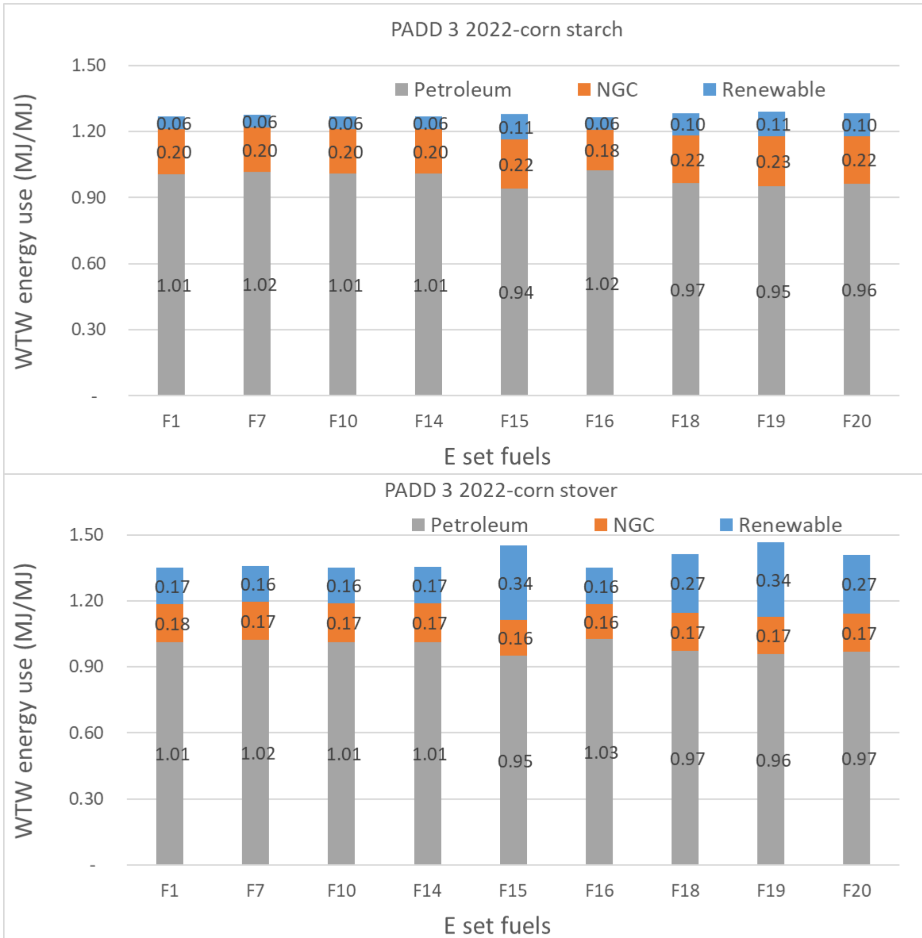


Figure 9-7. WTW Energy Uses of E Set Fuels (Domestic Gasolines) Produced in PADD 3 in 2022, with Ethanol from Corn Starch and Corn Stover, Respectively

Between the two ethanol sources, corn stover ethanol has higher renewable energy use and less natural gas and coal (NGC) energy use than starch ethanol. For each E set domestic gasoline (including both BAU and HOF finished gasoline), the difference in WTW petroleum energy use between the two ethanol sources is very small. Natural gas is used along the WTW E fuel production pathway, including corn growing, ethanol production, and refinery use (as process fuel and feed to SMR).

The energy use results for E set fuels in CA in 2022 with the two ethanol sources are shown in Figures 9-8 and 9-9. The data in the figures are also listed in Appendix 4 Table A4-4 (corn starch ethanol) and Table A4-5 (corn stover ethanol) for details.

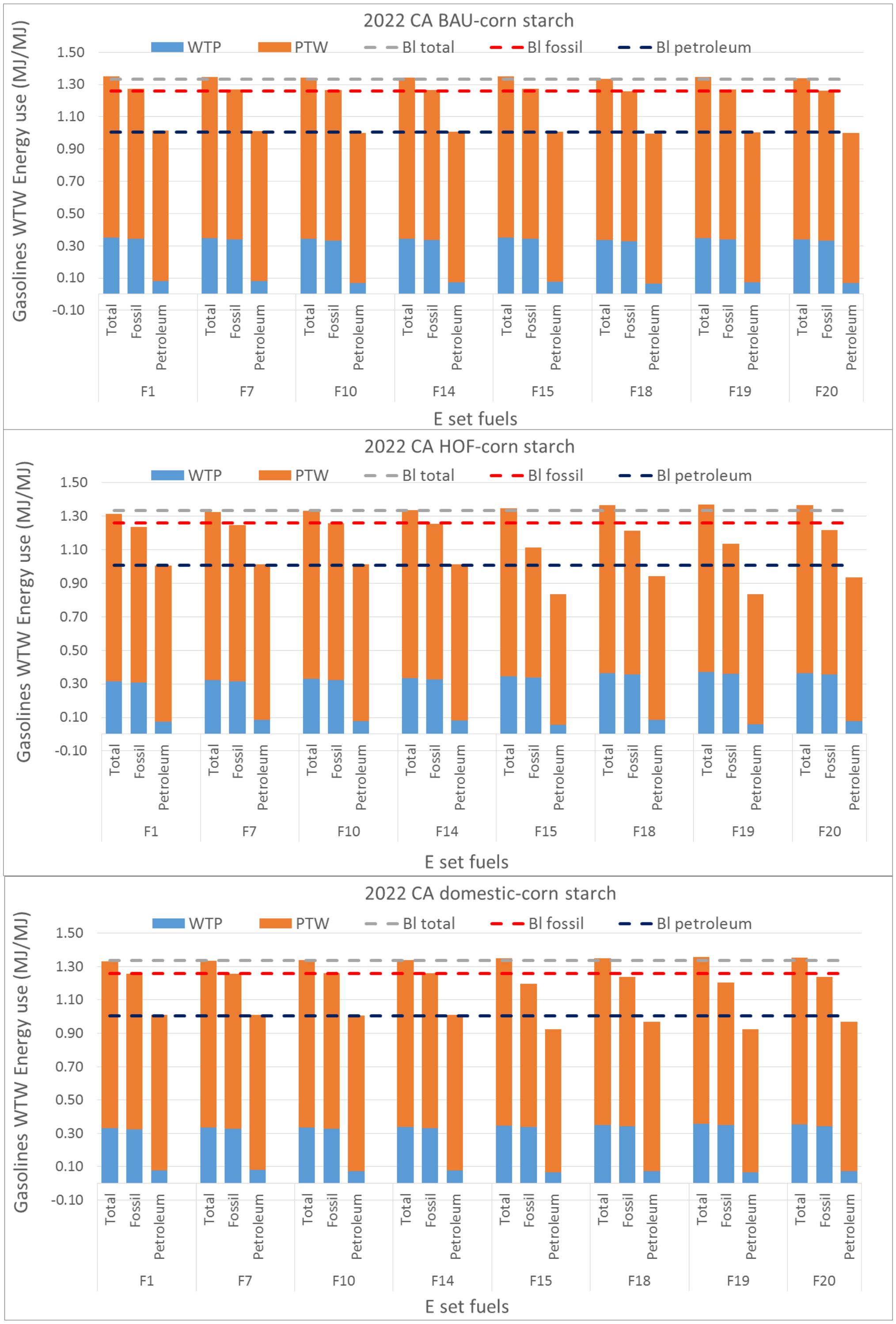


Figure 9-8. WTW Energy Use of E Set Fuels (BAU, HOF and Domestic Gasolines) with Corn Starch Ethanol in CA Refinery in 2022. Baseline (Bl) Uses Corn Starch Ethanol.

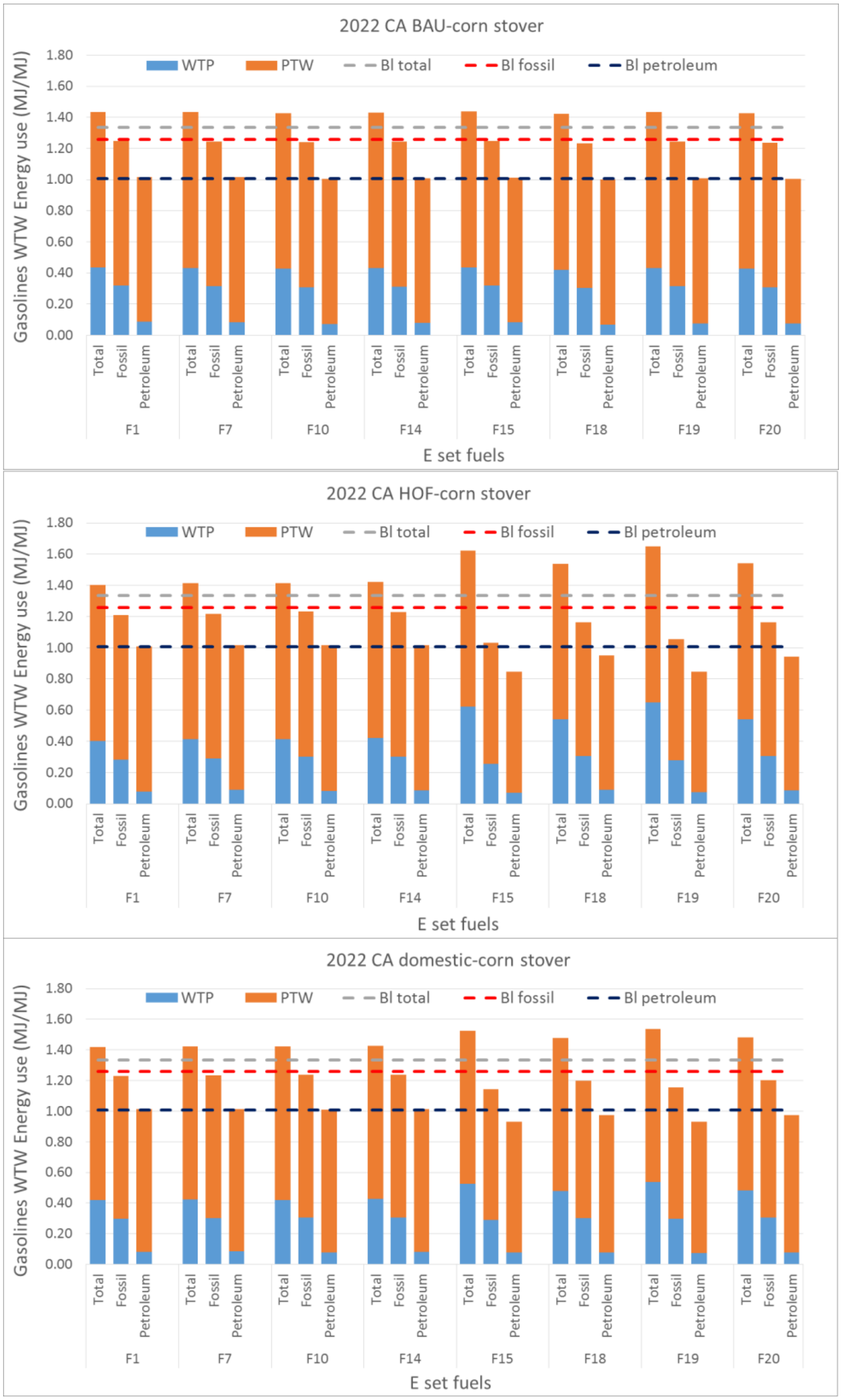


Figure 9-9. WTW Energy Use of E Set Fuels (BAU, HOF and Domestic Gasolines) with Corn Stover Ethanol in CA Refinery in 2022. Baseline (Bl) Uses Corn Starch Ethanol

E set fuels' WTW energy use in CA in 2022 is consistent with those in PADD 3 in 2022. The energy use (total, fossil, petroleum) of various E set BAU gasolines with ethanol from corn starch is similar to that of baselines. Fossil energy use for all the corn starch ethanol based HOF gasolines is lower than baselines, especially for F15, F18, F19, and F20. The F1, F7, F10, and F14 domestic gasolines have energy use (total, fossil and petroleum) similar to baselines, and the F15, F18, F19 and F20 domestic gasolines show lower energy use (fossil and petroleum) than baselines. Fossil energy and petroleum energy use for some of the E set gasolines with corn stover ethanol is much lower than baselines (which are based on using corn starch ethanol in 2022), while their total energy use is much higher than that of baseline.

The 2040 WTW energy uses of E set gasolines in PADD 3 and CA are shown in Figure 9-10 and Figure 9-11. The data in Figures 9-10 and 9-11 are also listed in Appendix 4 Table A4-6 (for both corn starch ethanol and corn stover ethanol) for details.

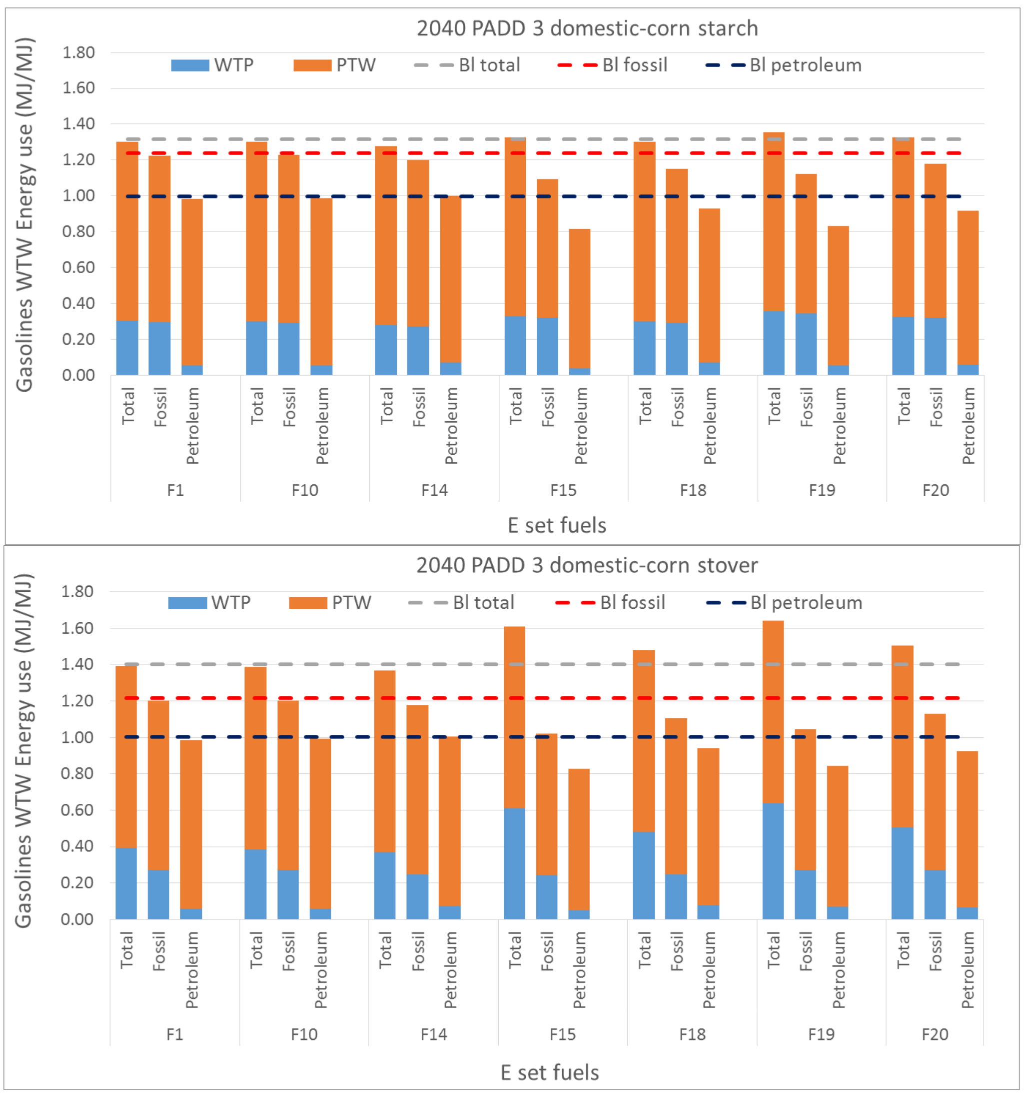


Figure 9-10. WTW Energy Uses of E Set fuels (Domestic Finished Gasolines) in PADD 3 in 2040. Dual Sets of Baselines Used with Corn Starch Ethanol and Corn Stover Ethanol, Respectively

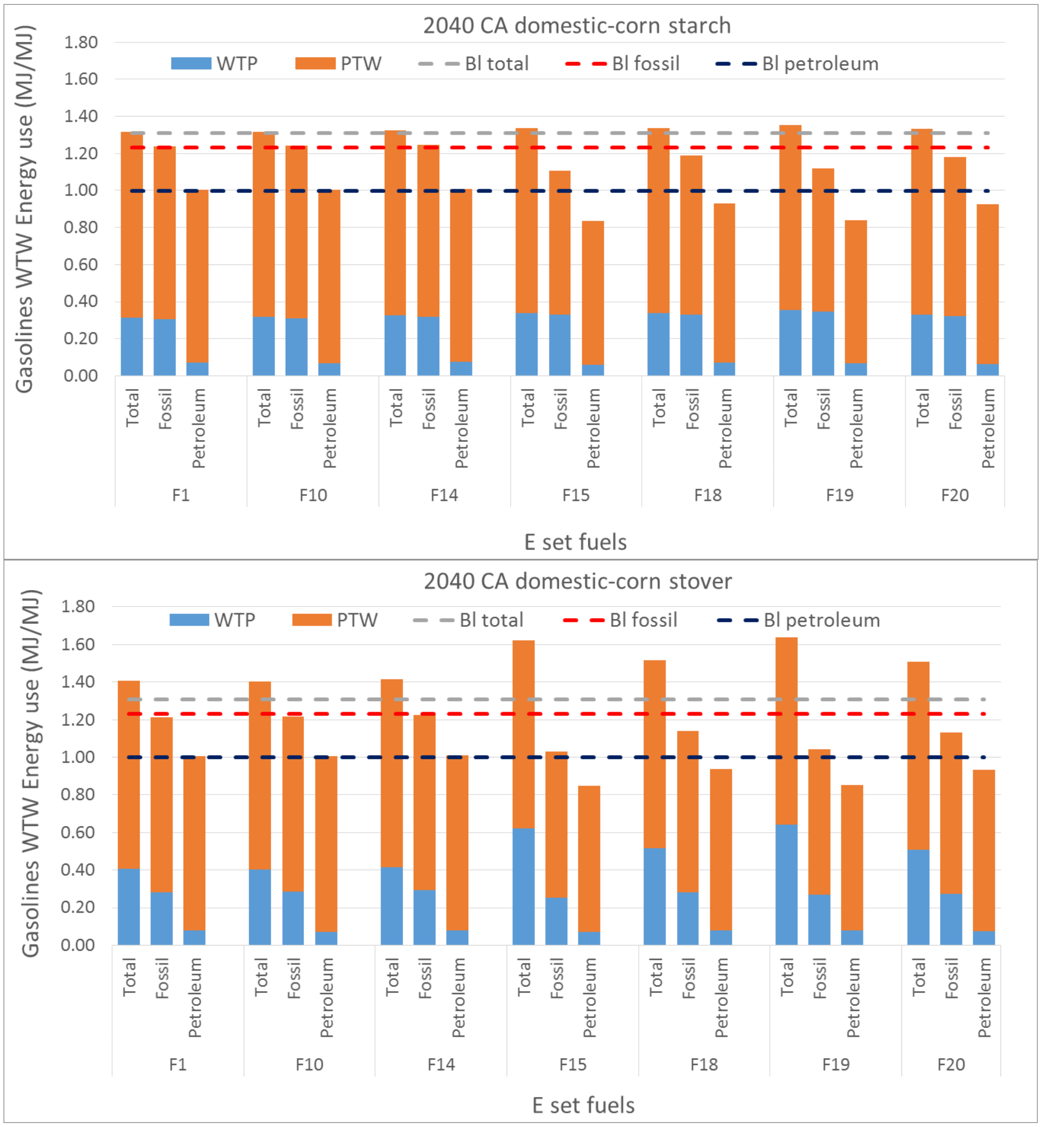


Figure 9-11. WTW Energy Uses of E Set Fuels (Domestic Finished Gasolines) in CA in 2040. Dual Sets of Baselines Used with Corn Starch Ethanol and Corn Stover Ethanol, Respectively

It is worth mentioning that in 2040, two sets of different baselines are used: one with ethanol from corn starch and one with ethanol from corn stover.

In each PADD/Region refinery, energy use in 2040 for E set domestic gasoline with ethanol from corn starch follow patterns similar to those in 2022. The domestic gasolines of F1, F10, and F14 have energy use (total, fossil and petroleum) similar to baselines (with corn starch ethanol) and the domestic gasolines of F15, F18, F19, and F20 show considerably lower energy use (fossil and petroleum) than baseline, although the total energy use for those fuels is considerably higher than baseline.

Unlike the 2022 comparison, in 2040, the E set gasolines with corn stover ethanol are compared with baselines that are also based on using corn stover ethanol. However, the patterns of their energy use are the same as in 2022: their use of fossil energy and petroleum energy is much lower than that of baselines, while their total energy use is higher than baseline.

9.1.2.2 Aggregate Refinery E Set Fuel GHG Emissions Per MJ of Fuel Used

As discussed in the gasoline energy intensity section earlier, for some fuels, burdens from exported gasoline are shifted back to HOF fuels. The burden is fairly small and is shown in Table 9-2. These burdens are included in the HOF fuel WTW GHG emissions. The GHG burdens from exported gasoline in 2040 for F15 are higher than that for the other fuels, but still small.

Table 9-2. Burden from Export Gasoline Added to HOF WTW GHG Emissions (g/MJ HOF)

Fuel	PADD 3 2022	CA 2022	PADD 3 2040	CA 2040
F1	0.000	0.000	0.000	0.072
F7	0.000	0.094	--	--
F10	0.000	0.007	0.000	0.000
F14	0.000	0.000	0.000	0.065
F15	0.000	0.000	0.368	0.745
F16	0.000	--	--	--
F18	0.000	0.000	0.000	0.076
F19	0.000	0.000	0.000	0.000
F20	0.000	0.000	0.000	0.000

WTW GHG emissions of E set fuels (BAU, HOF and domestic finished gasoline) in PADD 3 for ethanol from corn starch in 2022 are shown in Figure 9-12, broken into WTP and PTW stages. The burden from exported gasoline is added in the WTP stage.

Consistent with the trends of fossil energy and petroleum energy use, GHG emissions for E set BAU gasolines are similar to baselines. HOF gasolines with high ethanol blending have lower GHG emissions than baselines. The combined domestic gasolines for F15, F19, F18, and F20 show GHG reductions of about 1%–4% with high ethanol blending from corn starch.

Compared to the baseline with corn starch ethanol, all the E set gasolines (BAU, HOF and domestic finished gasolines) with corn stover ethanol show lower WTW GHG emissions. Consistent with the trends of fossil energy and petroleum energy use, E30 fuels (F15 and F19) and E20 fuels (F18 and F20) show greatest GHG emission reductions for the domestic gasoline pool (about 5%–10% lower than those of baseline fuel with corn starch ethanol), as shown in Figure 9-13.

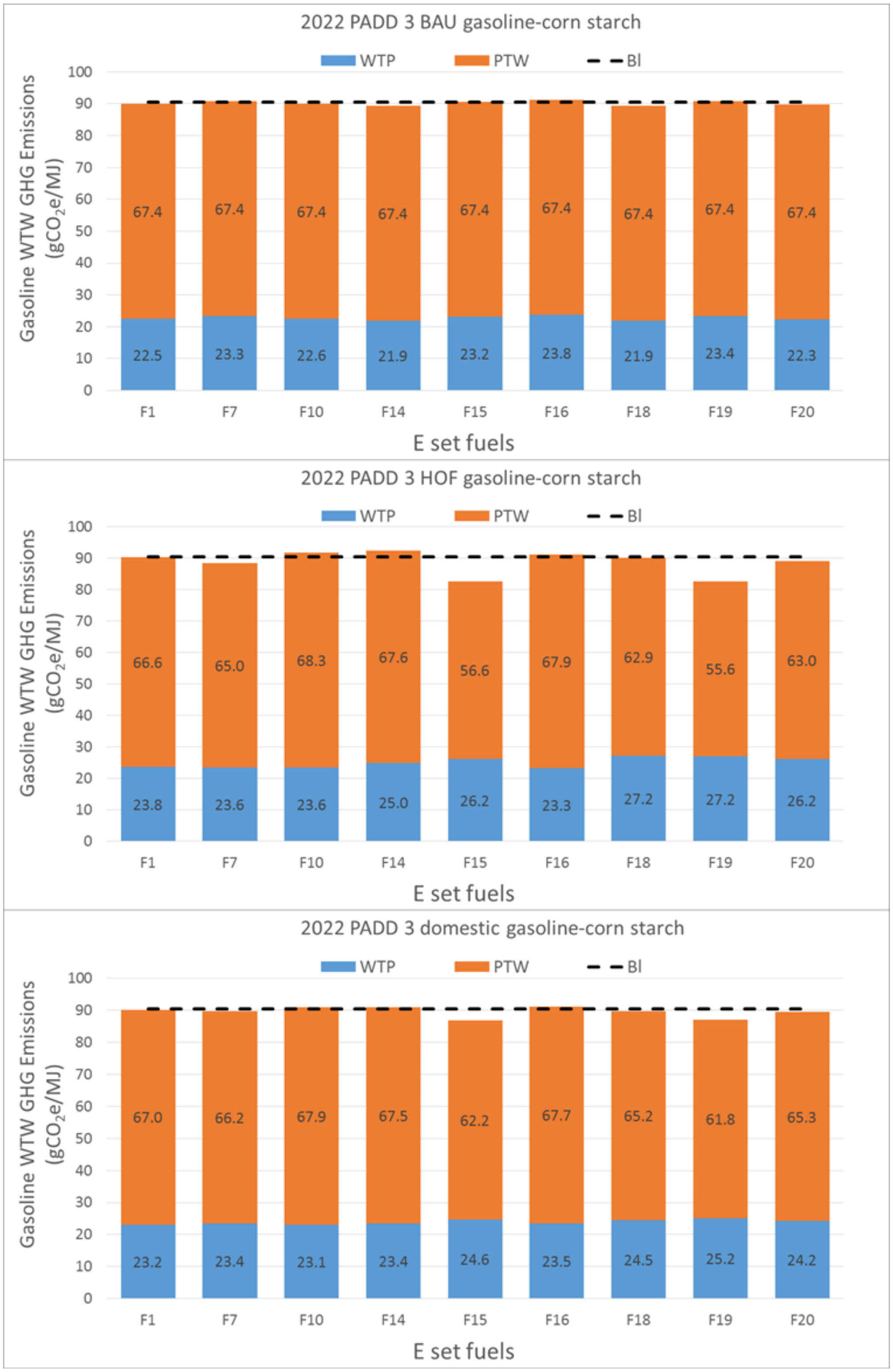


Figure 9-12. E Set fuels (BAU, HOF and Domestic Finished Gasolines) WTW GHG Emissions with Corn Starch Ethanol on the Per-MJ Basis in PADD 3 in 2022. Baseline Uses Corn Starch Ethanol

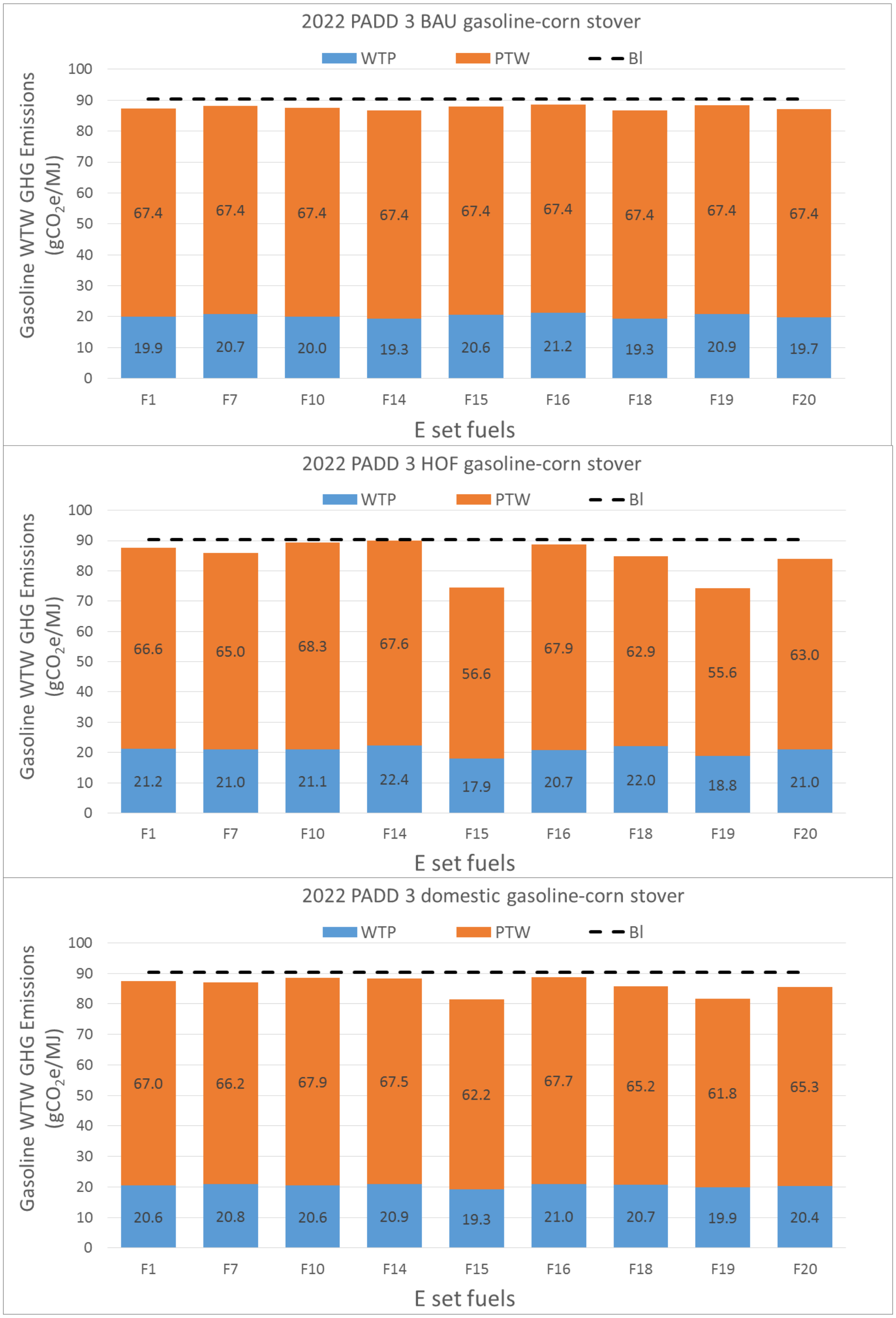


Figure 9-13. E Set Fuels (BAU, HOF and Domestic Finished Gasolines) WTW GHG Emissions with Corn Stover Ethanol on the Per-MJ Basis) in PADD 3 in 2022. Baseline Uses Corn Starch Ethanol

The WTW GHG emissions of E set gasoline with corn starch ethanol and corn stover ethanol in CA in 2022 are shown in Figures 9-14 and 9-15, respectively.

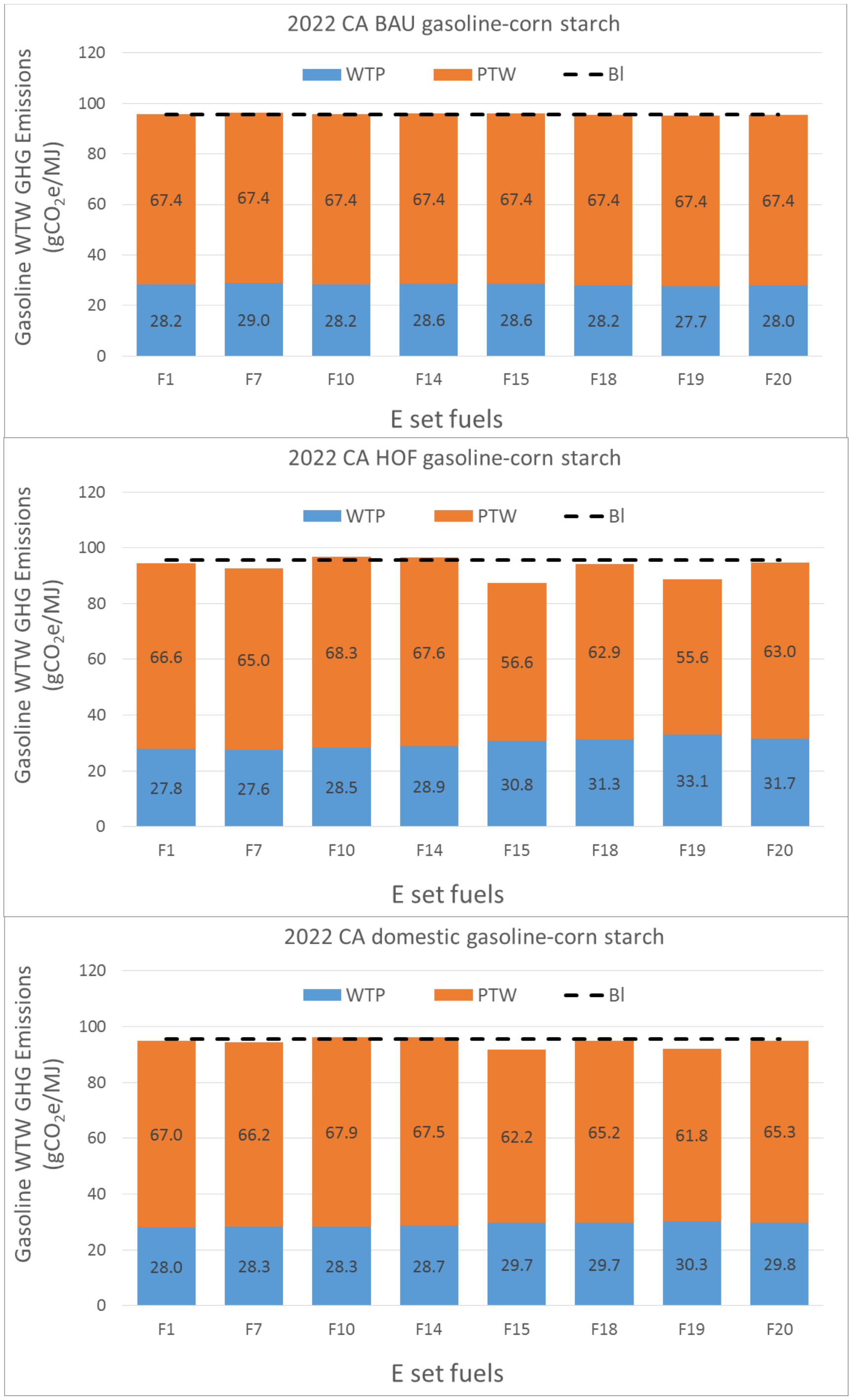


Figure 9-14. E Set Fuels (BAU, HOF and Domestic Finished Gasolines) WTW GHG Emissions with Corn Starch Ethanol on the Per-MJ Basis in CA in 2022. Baseline Uses Corn Starch Ethanol

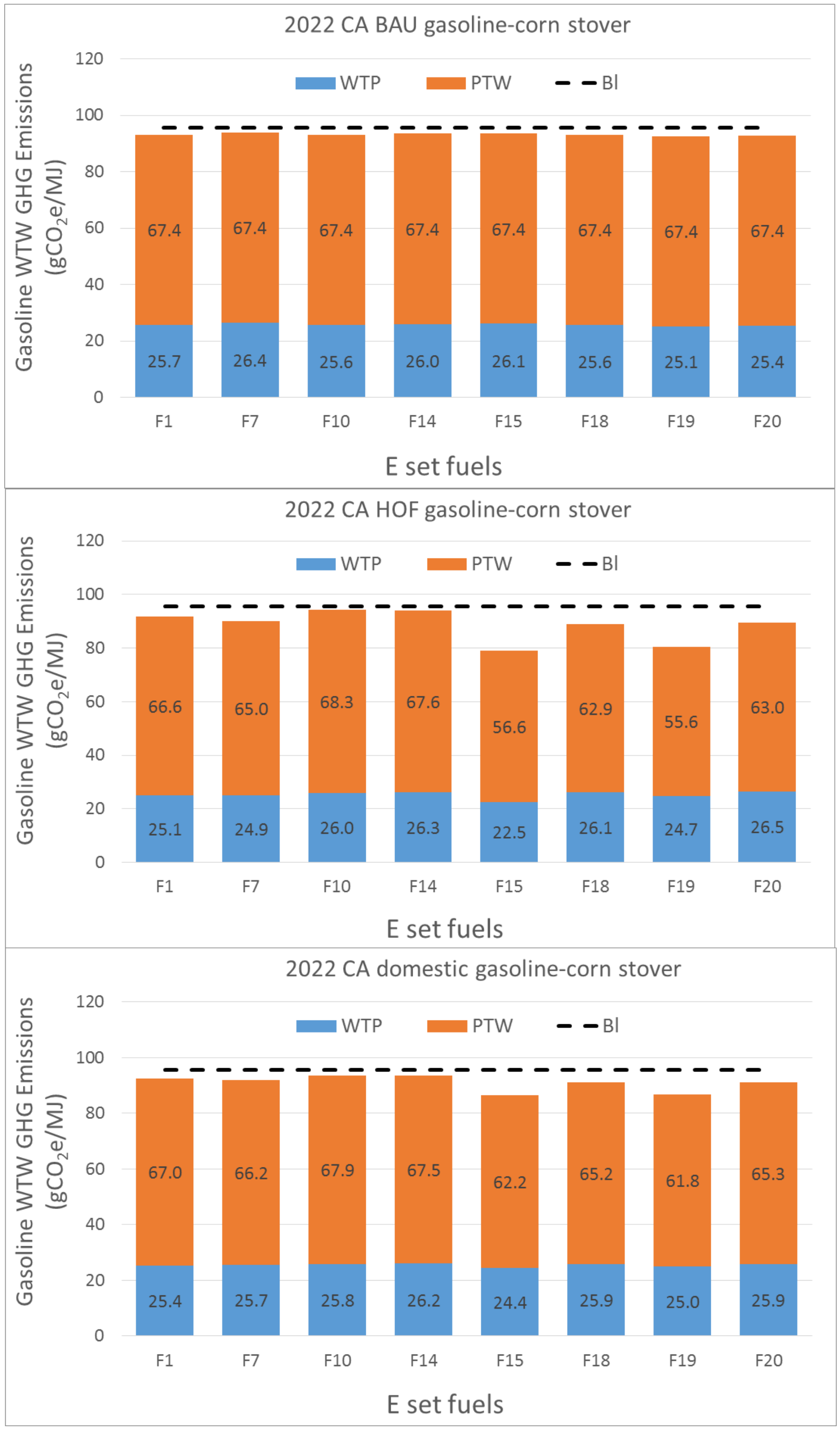


Figure 9-15. E Set Fuels (BAU, HOF and Domestic Finished Gasolines) WTW GHG Emissions with Corn Stover Ethanol on the Per-MJ Basis) in CA in 2022. Baseline Uses Corn Starch Ethanol

In 2040, the domestic finished gasoline pool contains HOF gasoline with 100% market share. For each E set fuel, WTW GHG emissions in CA are higher than GHG emissions in PADD 3, due to GHG difference in the WTP stage. Given that the WTP GHG emissions of ethanol are the same in PADD 3 and CA, the difference is attributed to higher WTP gasoline BOB GHG emissions in CA than in PADD 3. High GHG emissions in the CA refining process are caused by high hydrogen demand. Comparison of WTW GHG emissions for E set gasolines in CA with those of baselines shows that the relative trends are similar to those in PADD 3. See Figure 9-16 and Figure 9-17.

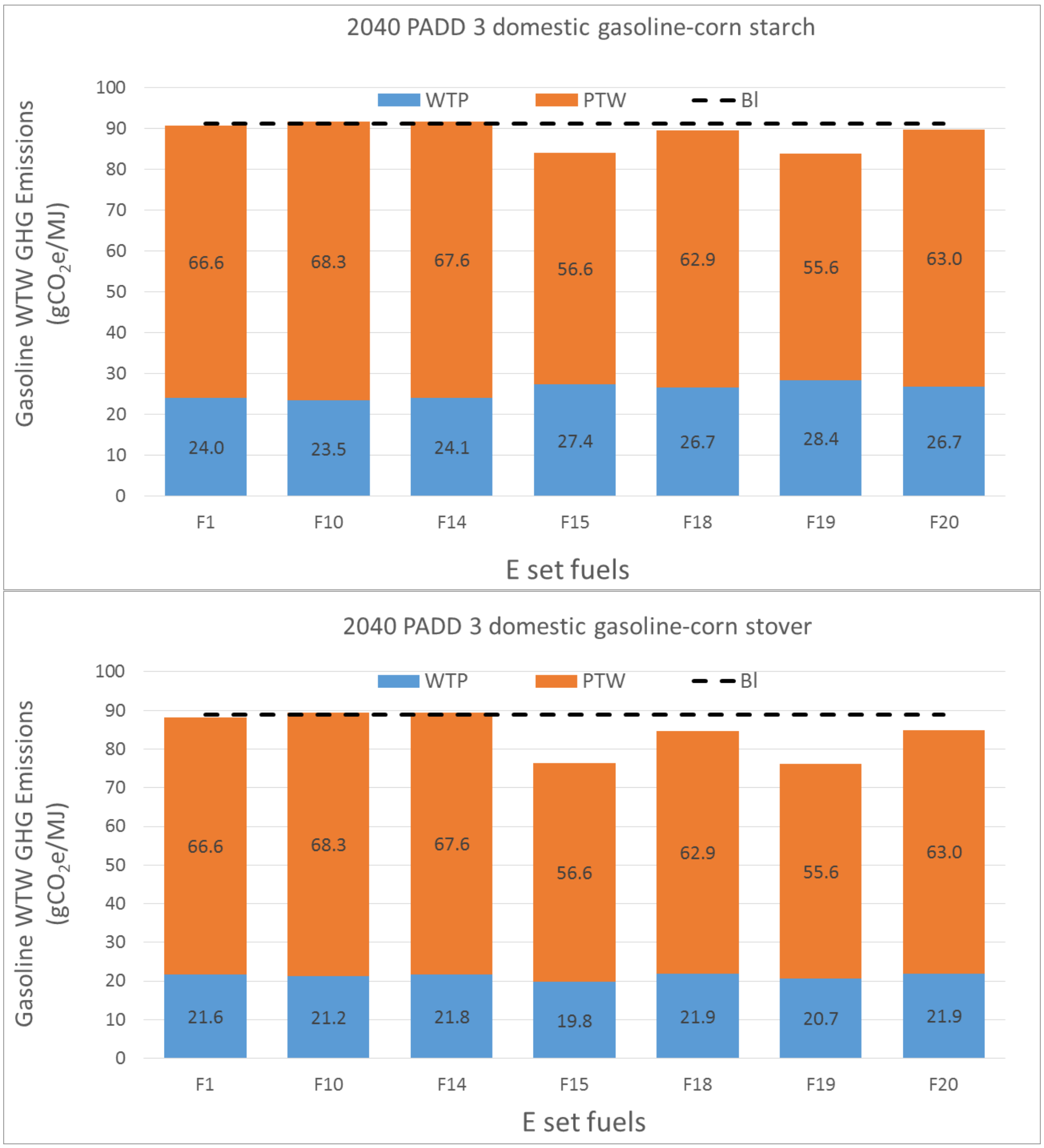


Figure 9-16. E Set Domestic Finished Gasolines WTW GHG Emissions in PADD 3 in 2040 with Corn Starch Ethanol and Corn Stover Ethanol, Respectively. Dual Sets of Baselines Used.

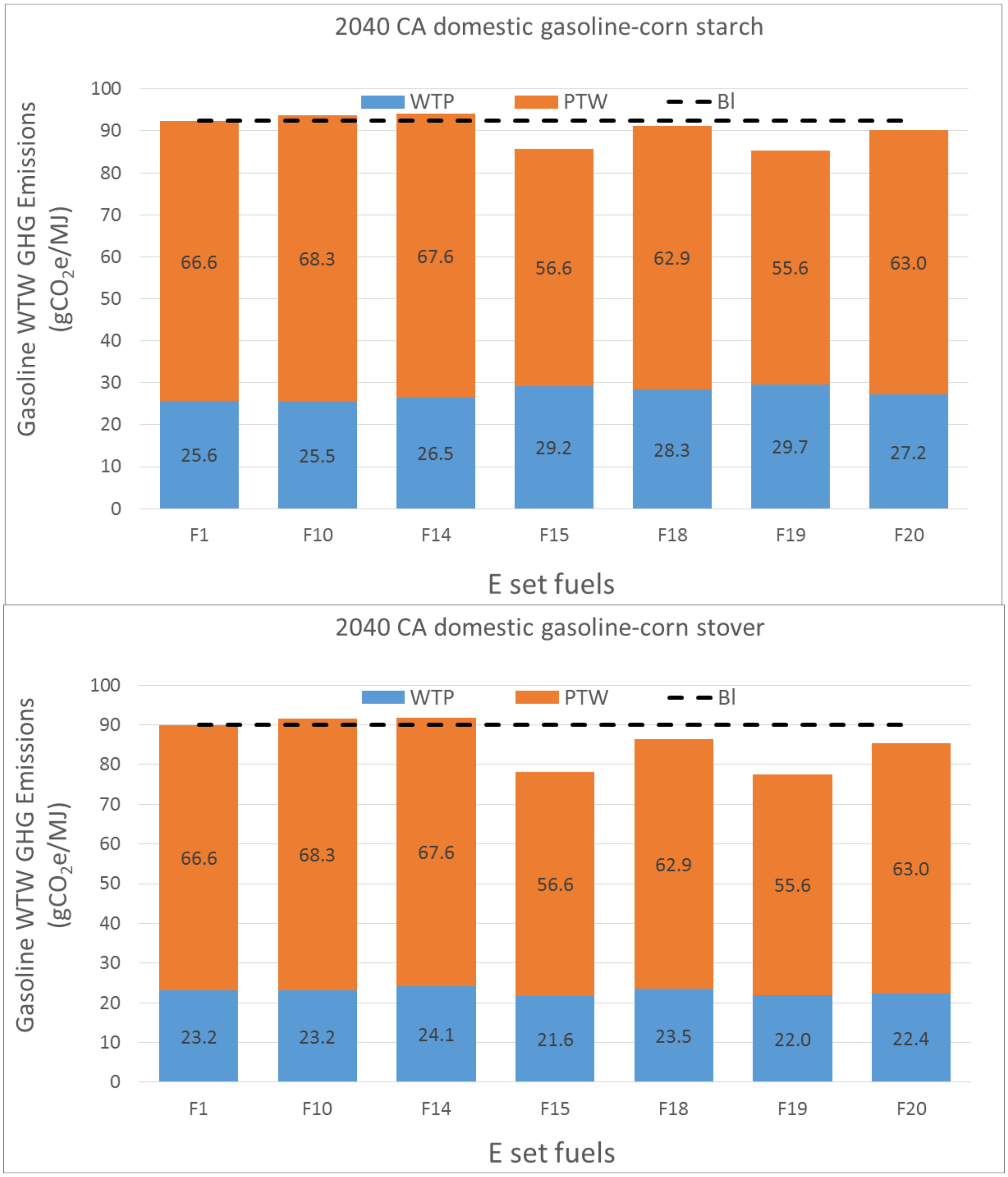


Figure 9-17. E Set Domestic Finished Gasolines WTW GHG Emissions in CA in 2040 with Corn Starch Ethanol and Corn Stover Ethanol, Respectively. Dual Sets of Baselines Used

In 2040, for E set fuels with high ethanol blending (E20 and E30), their GHG emission are compared with baseline with the same ethanol source, from corn starch or corn stover. In both PADD 3 and CA, with corn starch ethanol, the WTW GHG emissions of the E20 fuels (F18 and F20) are 1%–2% lower than baseline, and that of E30 fuels (F15 and F19) are about 4-5% lower than baseline. For corn stover ethanol, the WTW GHG emissions of the E20 fuels (F18 and F20) are 5% lower than baseline, and that of E30 fuels (F15 and F19) are about 9-10 % lower than baseline. In contrast, the E set fuels with low blending levels (F1, F10 and F14) show GHG emissions similar to or slightly higher than baselines because of their higher WTP GHG emissions. For each E set fuel, the change relative to the base cases is shown in Figure 9-18 for 2022. Note that the burden from exported gasoline is also taken into account.

E set domestic gasolines, with ethanol from either corn starch or corn stover, were compared to the baseline with corn starch ethanol for each Region in 2022. E set gasolines with corn stover ethanol have a much greater GHG reduction benefit than those with corn starch ethanol, as shown in Figure 9-18.

For 2040, two sets of baselines were compared to fuels with ethanol from corn starch and corn stover (Figure 9-19). In most cases, GHG emissions are reduced by producing high-octane bio-blended fuels. Fuel 10 and Fuel 14 show slightly higher WTW GHG emissions than base cases, because their BOB production has a slightly more energy intensive refining process. Fuel 15 and Fuel 19 show the greatest GHG reduction benefit (about 14%), primarily attributable to the diluting effect of their high bio-blend level (30%).

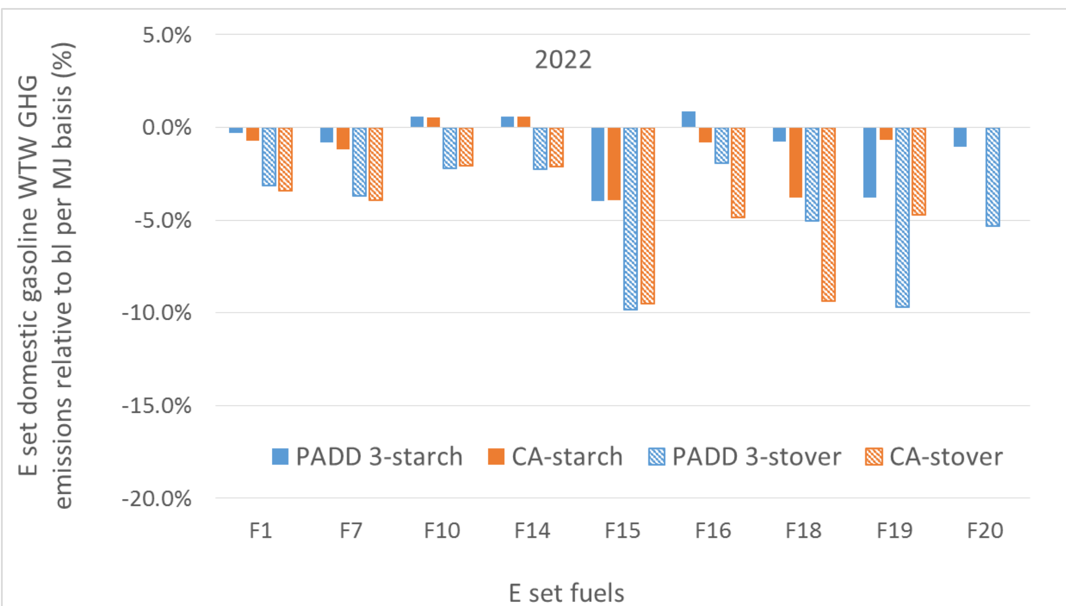


Figure 9-18. Comparison of PADD 3 and CA E Set Fuels WTW GHG Emissions to Those of Baselines in 2022 on the Per-MJ Basis. Baselines Use Corn Starch Ethanol

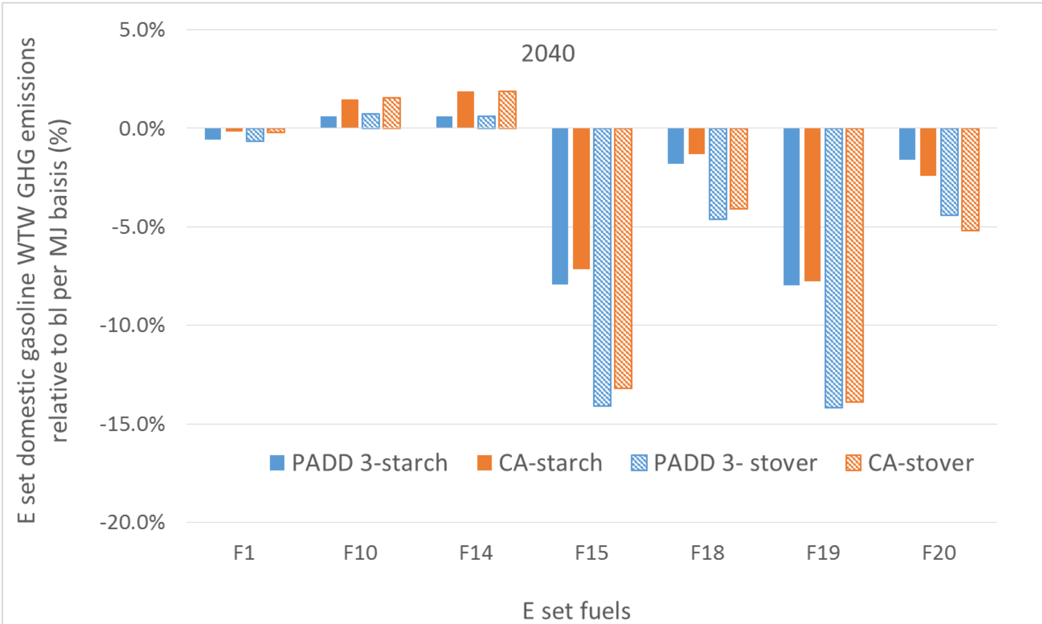


Figure 9-19. Comparison of PADD 3 and CA E Set Fuels WTW GHG Emissions to Those of Baselines in 2040 on the per-MJ Basis. Baselines Use Corn Starch Ethanol

9.1.2.3 Aggregate Refinery E Set Fuel WTW Energy Use Per Mile Driven

The WTW energy use of E set fuels in PADD 3 and CA refineries with varying ratios of RON increase required per unit of compression ratio increase 3.0 ON/CR, 3.7 ON/CR and 5.6 ON/CR, for both 2022 and 2040, were investigated. The values of 3.7 and 5.6 were measured in the knock screening study conducted at ORNL[4], while the value of 3.0 represents an aspirational case for a future better engine optimized for higher octane fuels [8]. The WTW energy use of E set BAU, HOF and domestic gasolines with corn starch ethanol in PADD 3 in 2022, with the value of 3.0 ON/CR, is shown in Figure 9-20. The data are also listed in Appendix 4 Table A4-7 for details.

As expected, for the E set BAU gasolines, energy use is similar to baseline. For HOF gasoline (all E set fuels except F1 and F10), all fuels have lower energy use than baselines due to projected fuel economy gains, and the reduction is greater for fuels with high ethanol blending levels. Combining BAU and HOF gasoline results gives us the energy use of the domestic gasolines. The energy use results of E set gasolines with corn stover ethanol are shown in Figure 9-21. The data are also listed in Appendix 4 Table A4-7 for details.

For total energy, for the higher octane, corn starch based fuels, the E10 fuels (F7, F14, and F16) have the highest total energy reductions relative to the baseline. The smallest total energy reductions are for the E20 (F18 and F20) and E30 (F15 and F19) fuels. For the corn stover ethanol case, the total energy required for all fuels is higher than the baseline, with the highest values for the E20 and E30 fuels. In terms of total energy consumption, the higher engine efficiencies of the E20 and E30 fuels are not sufficient to make up the difference with respect to the E10 fuels, which have lower WTP energy consumption.

The fossil and petroleum energy uses for BAU gasolines are similar to baselines, while HOF and domestic gasolines show much lower fossil energy and petroleum energy uses.

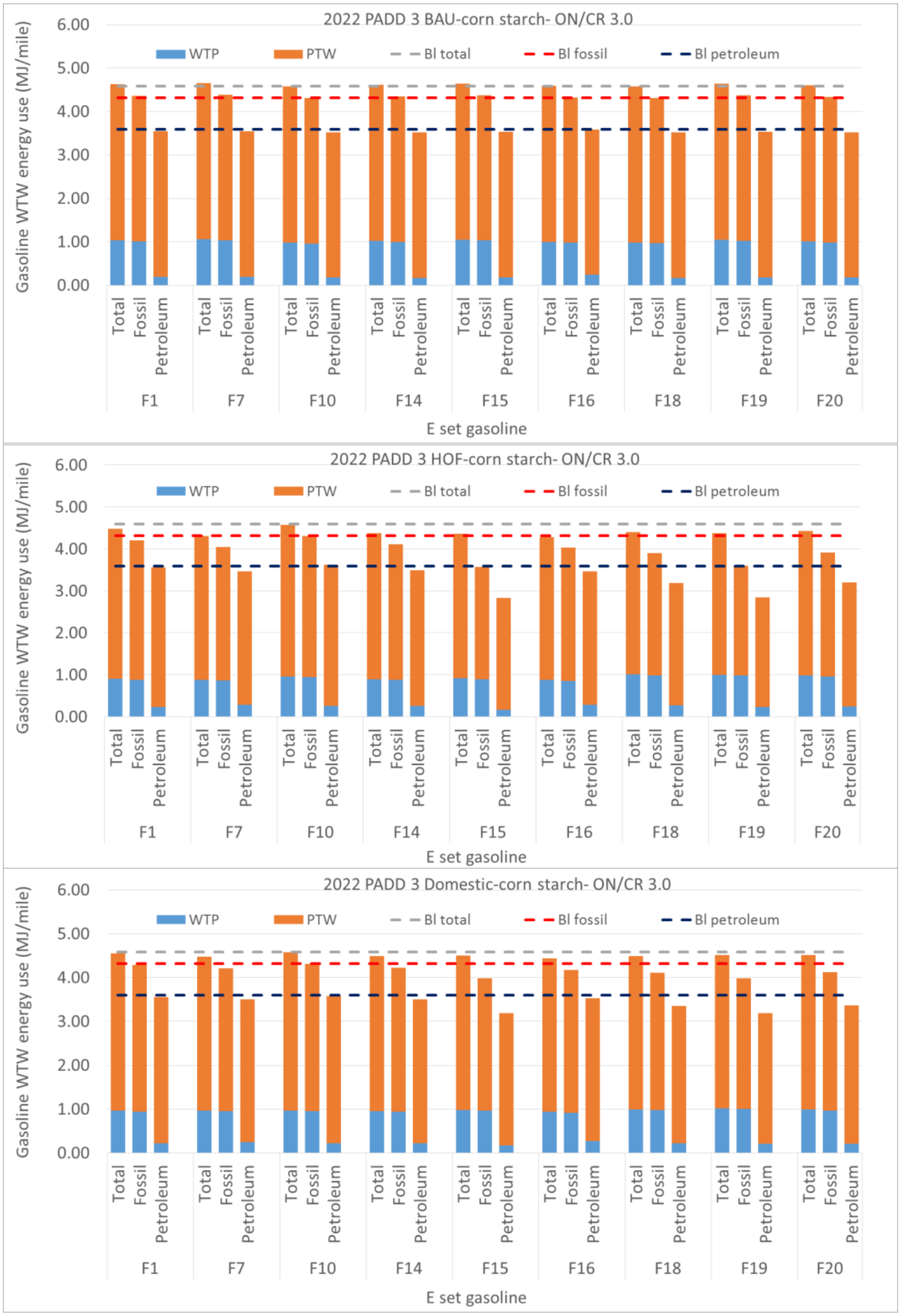


Figure 9-20. WTW Energy Use of E Set BAU, HOF and Domestic Finished Gasolines in PADD 3 in 2022 with Corn Starch Ethanol (for ON/CR of 3.0). Baselines Use Corn Starch Ethanol

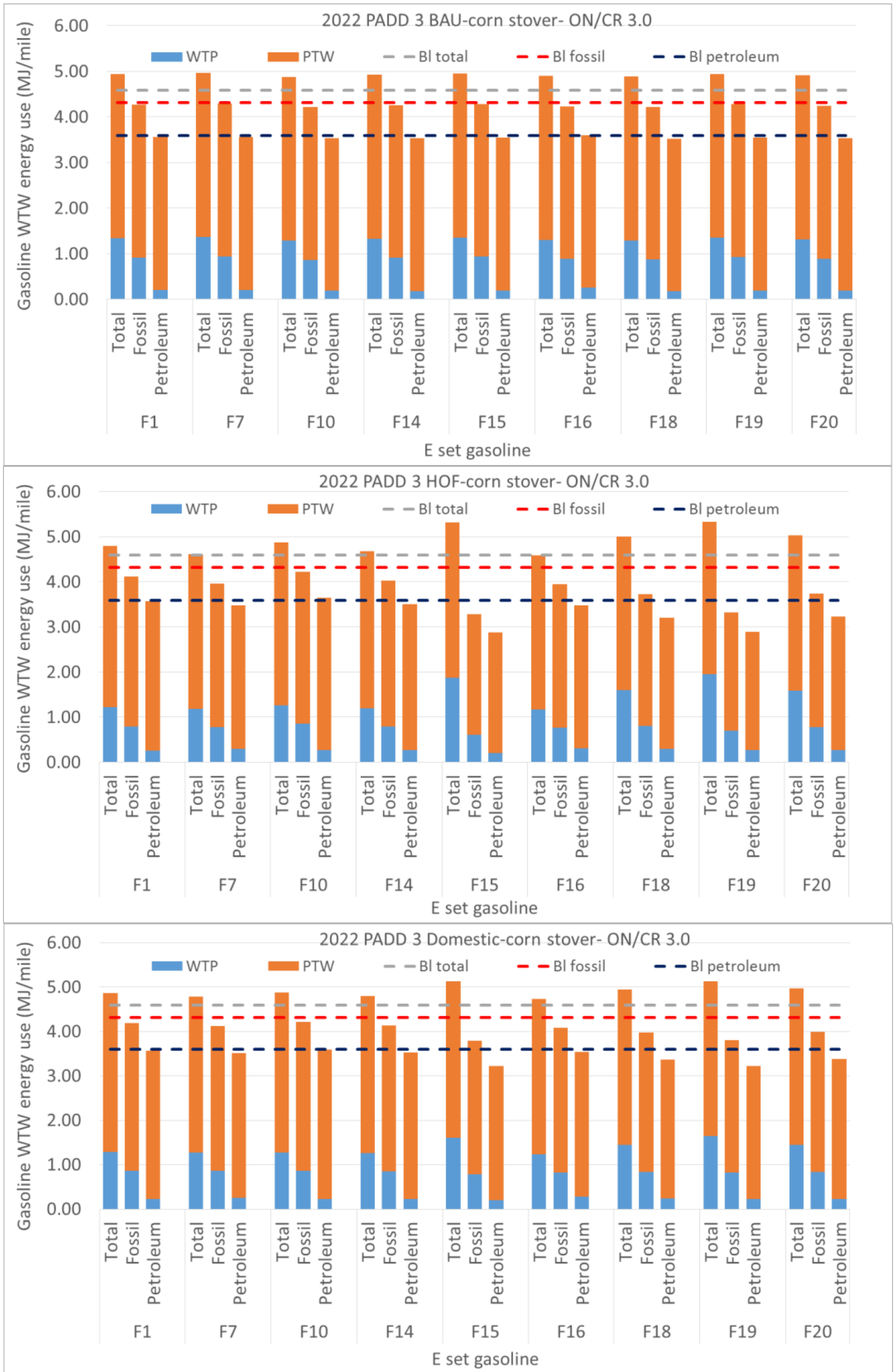


Figure 9-21. WTW Energy Use of E Set BAU, HOF and Domestic Finished Gasolines in PADD 3 in 2022 with Corn Stover Ethanol (for ON/CR of 3.0). Baselines Use Corn Starch Ethanol

A comparison of PADD 3 E set fuels energy uses to baselines (with corn starch ethanol) in 2022 is summarized in Figure 9-22.

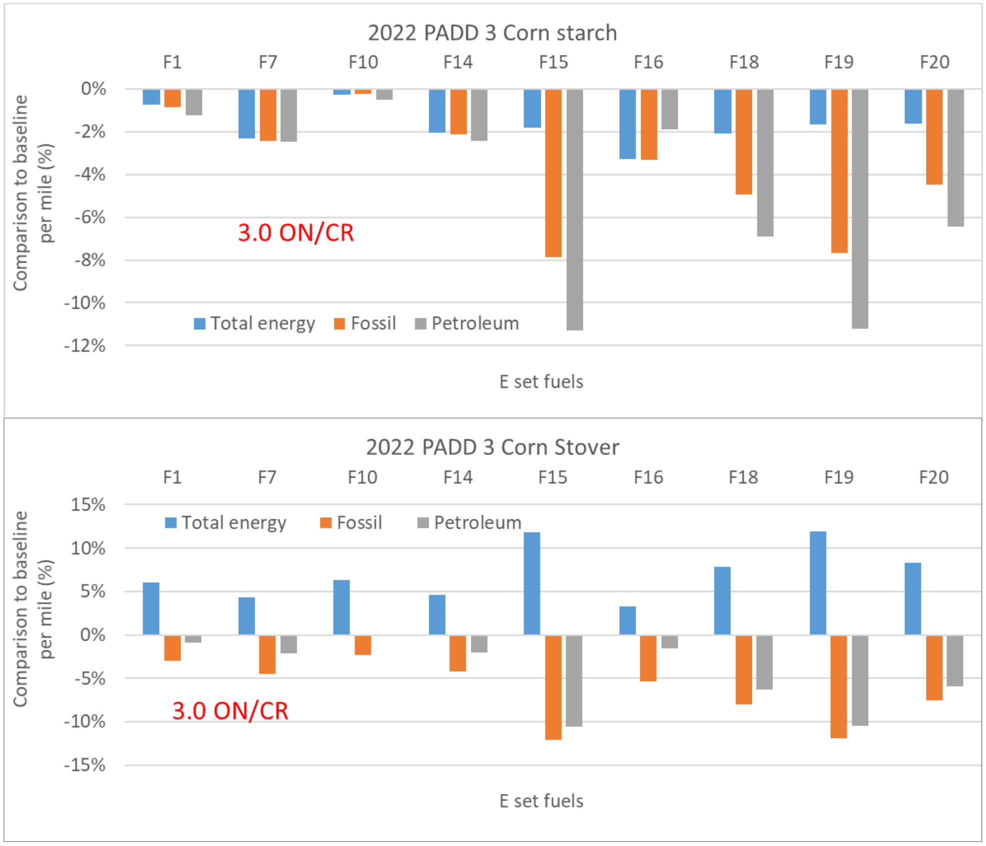


Figure 9-22. Comparison of E Set Fuels WTW Energy Use to Baseline Per Mile Basis in PADD 3 in 2022 (for ON/CR of 3.0). BaselinesUse Corn Starch Ethanol

Again, in 2022 only one baseline, with corn starch ethanol, is used for comparison with high-octane fuels. With corn starch ethanol, E30 fuels of F15 and F19 can reach an 8% fossil energy reduction and an 11% petroleum energy reduction, but a total energy reduction of less than 2%. With corn stover ethanol, F15 and F19 can reach a 12% reduction in fossil energy use per mile and a 10% reduction in petroleum energy use, but at the expense of a 12% increase in total energy use.

Energy use for the E set fuels in PADD 3 in 2022 with other fuel economy gains under 3.7 ON/CR and 5.6 ON/CR is shown in Appendix A4-8. Only the results of domestic finished gasolines are shown for brevity, as the patterns of BAU and HOF gasolines are similar to those in which the fuel economy is assumed with 3.0 ON/CR. A comparison to baselines is shown in Table 9-3.

Varying the ON/CR assumptions leads to rather small changes (about 0.5%) in the E set domestic gasoline's WTW energy use reduction, compared with baselines. The WTW energy use of E set domestic gasolines in CA in 2022 with ethanol from starch and stover, assuming 3 ON/CR, is shown in Figure 9-23 and 9-24. The data are also listed in Appendix 4 Table A4-9 for details.

Table 9-3. Comparison of E Set Fuels (Domestic Finished Gasolines) Energy Use (MJ/mile) to Baselines in PADD 3 in 2022, with projected Fuel Economy for 3.0 ON/CR, 3.7 ON/CR and 5.6 ON/CR. A Single Set of Baselines Used with Corn Starch Ethanol

2022 PADD 3 ON/CR 3.0 (ΔMJ/baseline Mile)						
	Corn Starch			Corn Stover		
	Total	Fossil	Petroleum	Total	Fossil	Petroleum
F1	-0.7%	-0.8%	-1.2%	6.1%	-2.9%	-0.9%
F7	-2.3%	-2.4%	-2.5%	4.3%	-4.5%	-2.1%
F10	-0.3%	-0.2%	-0.5%	6.4%	-2.3%	-0.1%
F14	-2.1%	-2.1%	-2.4%	4.6%	-4.2%	-2.1%
F15	-1.8%	-7.9%	-11.3%	11.9%	-12.1%	-10.5%
F16	-3.3%	-3.3%	-1.9%	3.3%	-5.4%	-1.5%
F18	-2.1%	-4.9%	-6.9%	7.8%	-8.0%	-6.3%
F19	-1.7%	-7.7%	-11.2%	11.9%	-11.9%	-10.4%
F20	-1.6%	-4.5%	-6.4%	8.4%	-7.6%	-5.9%

2022 PADD 3 ON/CR 3.7 (ΔMJ/baseline Mile)						
	Corn Starch			Corn Stover		
	Total	Fossil	Petroleum	Total	Fossil	Petroleum
F1	-0.7%	-0.8%	-1.2%	6.1%	-2.9%	-0.9%
F7	-2.0%	-2.1%	-2.1%	4.7%	-4.1%	-1.7%
F10	-0.3%	-0.2%	-0.5%	6.4%	-2.3%	-0.1%
F14	-1.8%	-1.8%	-2.1%	4.9%	-3.9%	-1.8%
F15	-1.5%	-7.6%	-11.0%	12.2%	-11.8%	-10.2%
F16	-2.9%	-3.0%	-1.5%	3.6%	-5.0%	-1.2%
F18	-1.7%	-4.6%	-6.6%	8.2%	-7.7%	-6.0%
F19	-1.3%	-7.3%	-10.9%	12.3%	-11.6%	-10.1%
F20	-1.3%	-4.2%	-6.1%	8.7%	-7.3%	-5.6%

2022 PADD 3 ON/CR 5.6 (ΔMJ/baseline Mile)						
	Corn Starch			Corn Stover		
	Total	Fossil	Petroleum	Total	Fossil	Petroleum
F1	-0.7%	-0.8%	-1.2%	6.1%	-2.9%	-0.9%
F7	-1.4%	-1.5%	-1.6%	5.3%	-3.6%	-1.2%
F10	-0.3%	-0.2%	-0.5%	6.4%	-2.3%	-0.1%
F14	-1.3%	-1.4%	-1.7%	5.4%	-3.5%	-1.3%
F15	-1.1%	-7.2%	-10.7%	12.6%	-11.5%	-9.9%
F16	-2.3%	-2.4%	-0.9%	4.3%	-4.4%	-0.6%
F18	-1.1%	-4.0%	-6.0%	8.8%	-7.1%	-5.4%
F19	-0.7%	-6.8%	-10.4%	13.0%	-11.0%	-9.6%
F20	-0.8%	-3.7%	-5.7%	9.2%	-6.8%	-5.1%

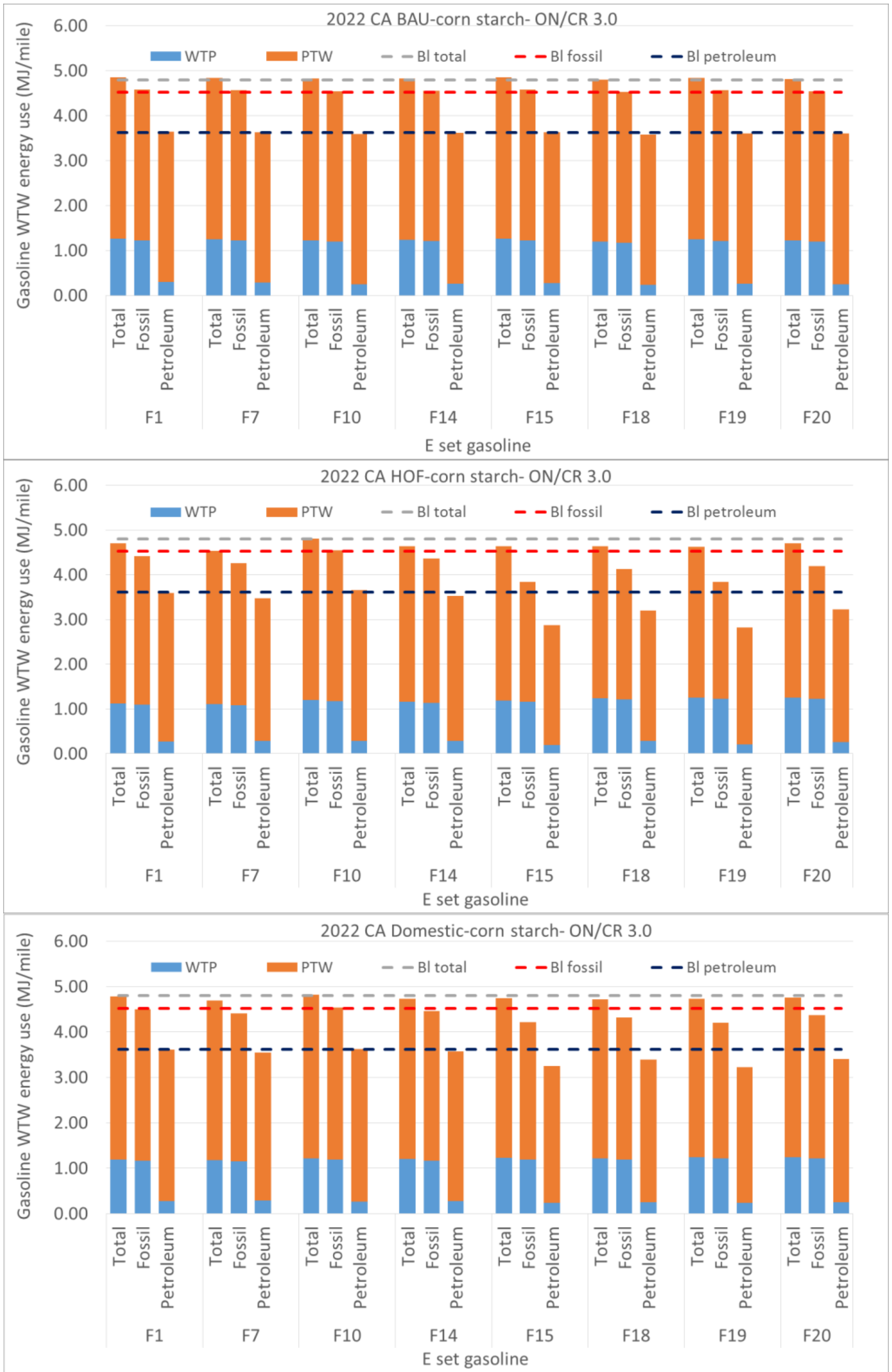


Figure 9-23. WTW Energy Use of E Set BAU, HOF and Domestic Finished Gasolines in CA in 2022 with Corn Starch Ethanol (for ON/CR of 3.0). Baselines Use Corn Starch Ethanol

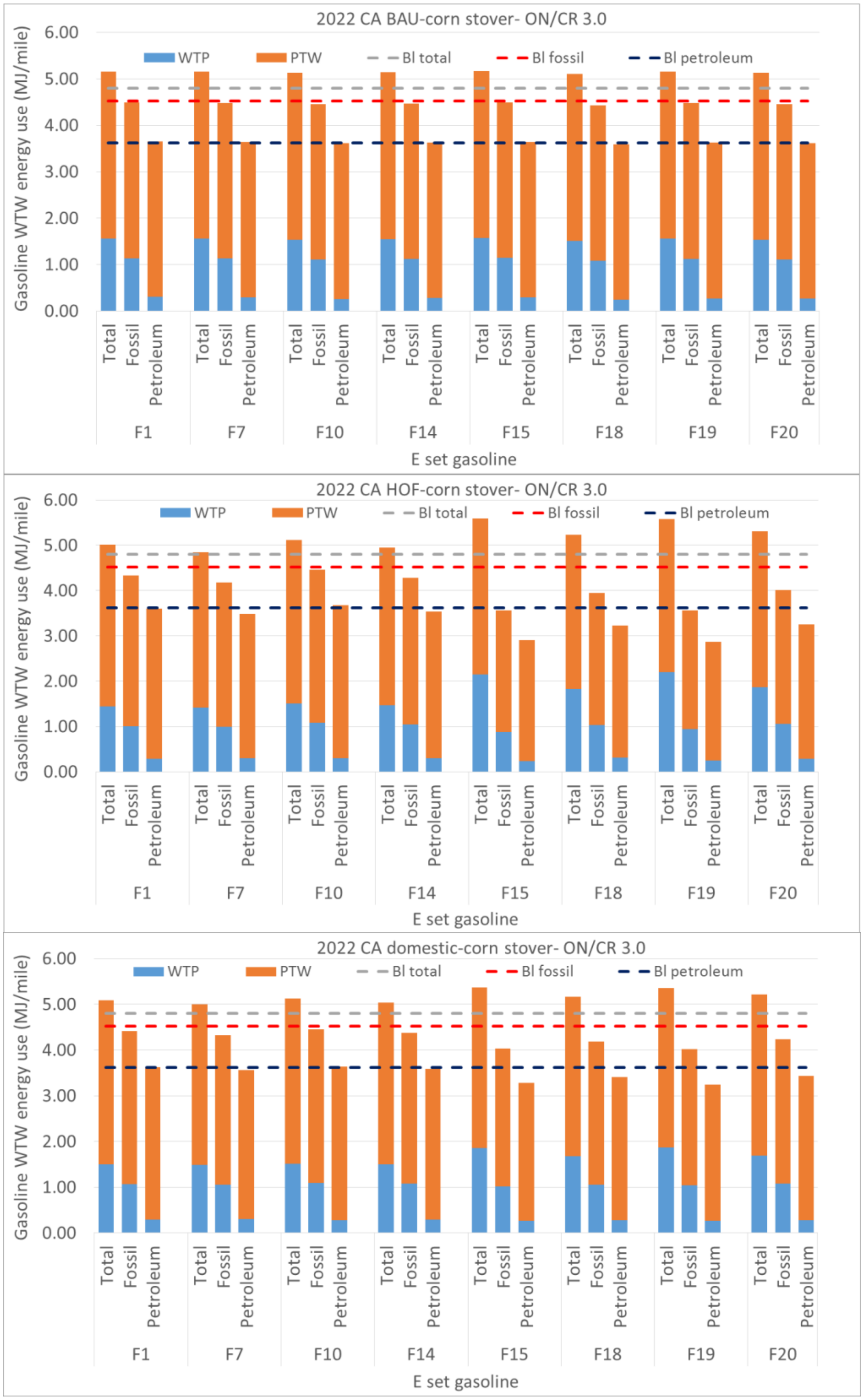


Figure 9-24. WTW Energy Use of E Set BAU, HOF and Domestic Finished Gasolines in CA in 2022 with Corn Stover Ethanol (for ON/CR of 3.0). Baselines Use Corn Starch Ethanol

Fo each E set gasoline, the WTW energy use in CA is higher than in PADD 3, because of the more energy intensive refining process in CA. Nonetheless, the patterns of E set gasoline energy use compared with baselines in CA are similar to those in PADD 3.

The relative changes of E set domestic gasoline WTW energy use per mile in CA in 2022 compared with baselines are summarized in Figure 9-25.

The patterns of relative energy changes in CA are similar to those in PADD 3. Although corn starch ethanol cases show greater reductions in petroleum energy use, corn stover ethanol cases show greater reductions in fossil energy use.

Energy use results for ON/CR of 3.7 and 5.6 are listed in Appendix 4 in Table A4-10. A comparison of WTW energy changes to baselines is shown in Table 9-4.

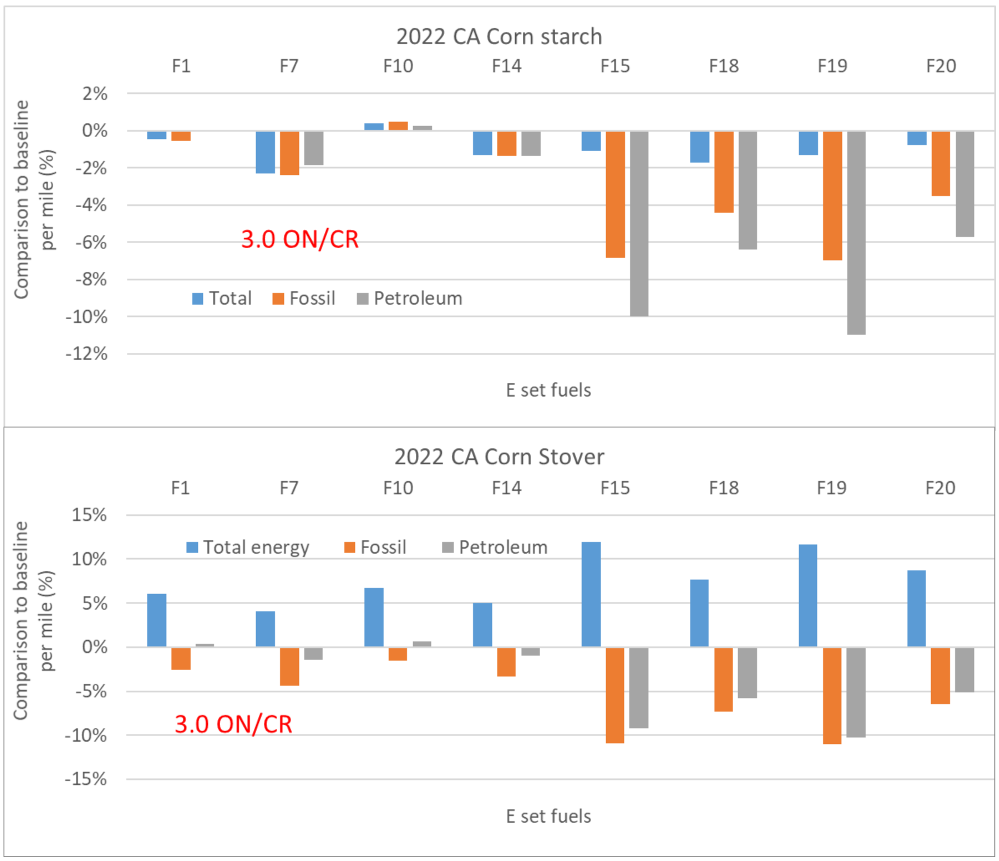


Figure 9-25. The Relative Changes of E Set Domestic Finished Gasolines WTW Energy Uses to Baselines in CA in 2022 (for ON/CR of 3.0). Baselines Use Corn Starch Ethanol

Table 9-4. Comparison of E Set Fuels (Domestic Finished Gasolines) Energy Uses to Baselines in PADD 3 in 2022 (for ON/CR of 3.0, 3.7 and 5.6). Baselines Use with Corn Starch Ethanol

	2022 CA ON/CR of 3.0 (ΔMJ/baseline Mile)					
	Corn Starch			Corn Stover		
	Total	Fossil	Petroleum	Total	Fossil	Petroleum
F1	-0.5%	-0.5%	0.0%	6.0%	-2.6%	0.3%
F7	-2.3%	-2.4%	-1.8%	4.0%	-4.4%	-1.5%
F10	0.4%	0.5%	0.2%	6.7%	-1.5%	0.6%
F14	-1.3%	-1.4%	-1.4%	5.0%	-3.3%	-1.0%
F15	-1.1%	-6.9%	-10.0%	12.0%	-10.9%	-9.3%
F18	-1.7%	-4.4%	-6.4%	7.7%	-7.4%	-5.8%
F19	-1.3%	-7.0%	-11.0%	11.7%	-11.0%	-10.2%
F20	-0.8%	-3.5%	-5.7%	8.7%	-6.4%	-5.2%

	2022 CA On/CR of 3.7 (ΔMJ/baseline Mile)					
	Corn Starch			Corn Stover		
	Total	Fossil	Petroleum	Total	Fossil	Petroleum
F1	-0.5%	-0.5%	0.0%	6.0%	-2.6%	0.3%
F7	-2.0%	-2.1%	-1.5%	4.4%	-4.0%	-1.1%
F10	0.4%	0.5%	0.2%	6.7%	-1.5%	0.6%
F14	-1.0%	-1.1%	-1.0%	5.4%	-3.0%	-0.7%
F15	-0.8%	-6.6%	-9.7%	12.3%	-10.6%	-9.0%
F18	-1.4%	-4.1%	-6.0%	8.1%	-7.0%	-5.5%
F19	-1.0%	-6.7%	-10.7%	12.1%	-10.7%	-9.9%
F20	-0.5%	-3.2%	-5.4%	9.1%	-6.1%	-4.9%

	2022 CA ON/CR of 5.6 (ΔMJ/baseline Mile)					
	Corn Starch			Corn Stover		
	Total	Fossil	Petroleum	Total	Fossil	Petroleum
F1	-0.5%	-0.5%	0.0%	6.0%	-2.6%	0.3%
F7	-1.4%	-1.5%	-0.9%	5.0%	-3.5%	-0.6%
F10	0.4%	0.5%	0.2%	6.7%	-1.5%	0.6%
F14	-0.6%	-0.6%	-0.6%	5.8%	-2.6%	-0.3%
F15	-0.4%	-6.2%	-9.4%	12.8%	-10.3%	-8.6%
F18	-0.8%	-3.5%	-5.5%	8.8%	-6.5%	-4.9%
F19	-0.4%	-6.1%	-10.2%	12.8%	-10.2%	-9.4%
F20	0.0%	-2.7%	-5.0%	9.6%	-5.7%	-4.4%

Varying of the ON/CR assumption leads to rather small changes in E set domestic finished gasoline WTW energy use reductions, compared with baselines. Overall, in 2022 the energy use reductions in CA cases are slightly less than in PADD 3 cases.

In 2040, all domestic gasolines are HOF. With patterns similar to 2022's, the energy use results are listed in Tables 9-5 and 9-6 for PADD 3 cases and CA cases, respectively with ON/CR of 3.0. The results with ON/CR of 3.7 and 5.6 are shown in Appendix 4 in Table A4-11 and Table A4-12.

Table 9-5. WTW Energy Use of E Set Domestic Finished Gasolines in PADD 3 in 2040, with Ethanol from Starch and Stover, Respectively (for ON/CR of 3.0)

2040 PADD 3 Domestic Gasoline, ON/CR of 3.0												
Ethanol	Corn Starch (MJ/Mile)						Corn Stover (MJ/Mile)					
Energy	Total		Fossil		Petroleum		Total		Fossil		Petroleum	
Fuel	WTP	PTW	WTP	PTW	WTP	PTW	WTP	PTW	WTP	PTW	WTP	PTW
Baseline	1.11	3.52	1.08	3.28	0.24	3.28	1.42	3.52	1.00	3.28	0.25	3.28
F1	1.06	3.51	1.04	3.26	0.19	3.26	1.38	3.51	0.95	3.26	0.20	3.26
F10	1.07	3.54	1.04	3.31	0.19	3.31	1.37	3.54	0.96	3.31	0.21	3.31
F14	0.95	3.41	0.92	3.17	0.24	3.17	1.25	3.41	0.84	3.17	0.25	3.17
F15	1.10	3.38	1.08	2.62	0.13	2.62	2.06	3.38	0.82	2.62	0.17	2.62
F18	1.01	3.33	0.98	2.86	0.24	2.86	1.60	3.33	0.82	2.86	0.27	2.86
F19	1.18	3.31	1.15	2.56	0.18	2.56	2.12	3.31	0.90	2.56	0.23	2.56
F20	1.10	3.38	1.08	2.91	0.20	2.91	1.70	3.38	0.92	2.91	0.23	2.91

Table 9-6. WTW Energy Use of E Set Domestic Gasolines in CA in 2040, with Ethanol from Starch and Stover, Respectively (for ON/CR of 3.0)

2040 CA Domestic Gasoline, ON/CR of 3.0												
Ethanol	Corn Starch (MJ/Mile)						Corn Stover (MJ/Mile)					
Energy	Total		Fossil		Petroleum		Total		Fossil		Petroleum	
Fuel	WTP	PTW	WTP	PTW	WTP	PTW	WTP	PTW	WTP	PTW	WTP	PTW
Baseline	1.09	3.52	1.06	3.28	0.24	3.28	1.39	3.52	0.98	3.28	0.25	3.28
F1	1.11	3.51	1.08	3.26	0.26	3.26	1.42	3.51	0.99	3.26	0.27	3.26
F10	1.12	3.54	1.09	3.31	0.24	3.31	1.42	3.54	1.01	3.31	0.26	3.31
F14	1.11	3.41	1.08	3.17	0.26	3.17	1.41	3.41	1.00	3.17	0.28	3.17
F15	1.14	3.38	1.11	2.62	0.2	2.62	2.1	3.38	0.86	2.62	0.24	2.62
F18	1.13	3.33	1.1	2.86	0.23	2.86	1.72	3.33	0.94	2.86	0.26	2.86
F19	1.18	3.31	1.15	2.56	0.22	2.56	2.12	3.31	0.89	2.56	0.26	2.56
F20	1.12	3.38	1.09	2.91	0.22	2.91	1.72	3.38	0.93	2.91	0.25	2.91

In 2040, all the E set fuels in PADD 3 with corn starch ethanol show energy use reductions relative to baselines (See Figure 9-26). F15 and F19 (both E30) show the greatest reductions: over 10% for fossil energy use and over 20% for petroleum energy use, but less than 3% total energy use reduction relative to baseline. With corn stover ethanol, these two fuels show the greatest fossil energy use reduction of about 17%, and the greatest petroleum energy use reduction of about 20%, but the greatest total energy use increase of over 10%. The F14 E10 fuel is the only fuel to have measurable reductions in total energy use for both corn starch and corn stover cases. The impact of fuel economy changes (due to different ON/CR ratio assumptions) on energy use reductions is small.

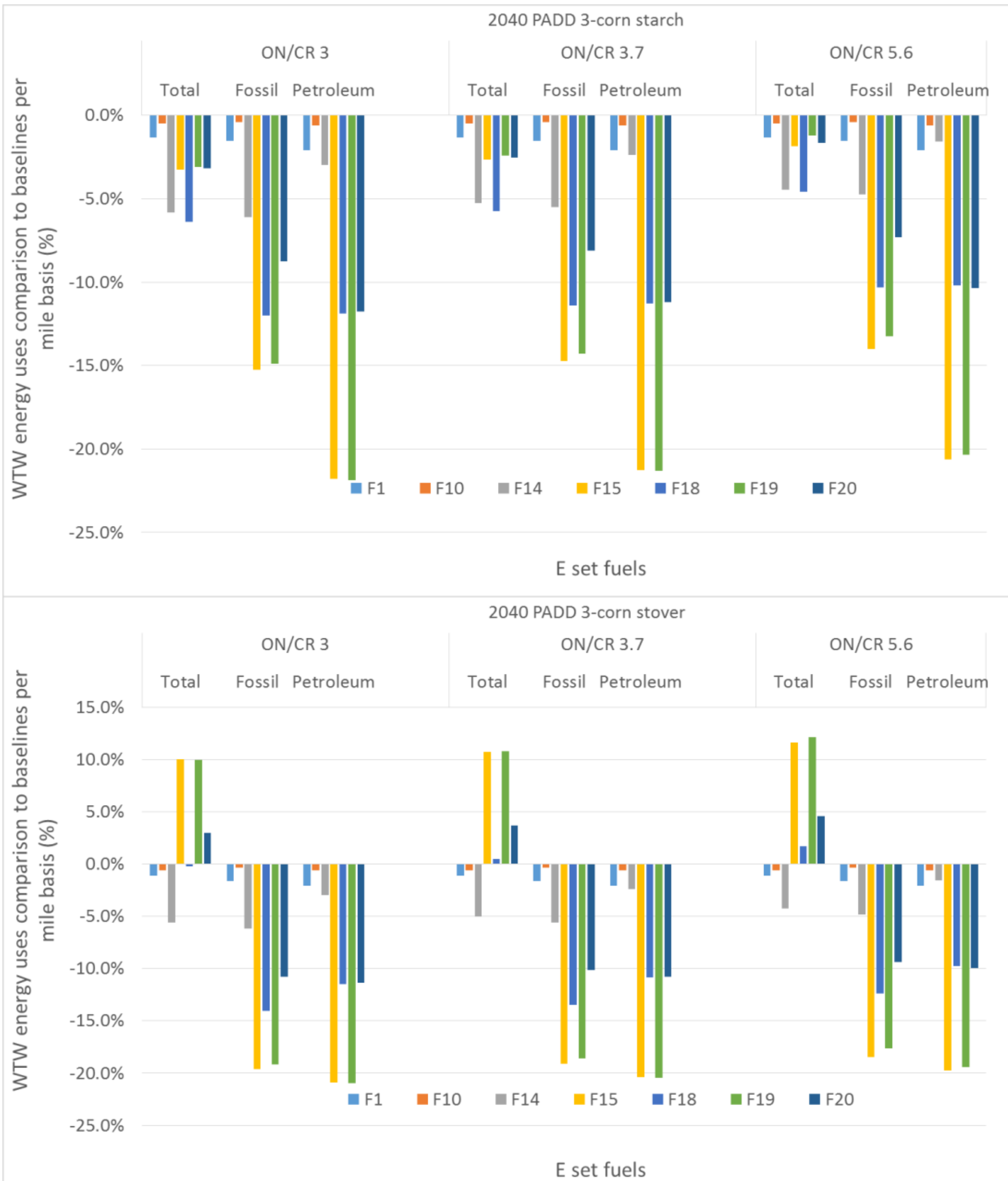


Figure 9-26. Comparison of E Set Domestic Gasolines (with Corn Starch Ethanol and Corn Stover Ethanol) Energy Uses per Mile to Baselines in PADD 3 in 2040 (for ON/CR 3.0, 3.7, and 5.6). Dual Sets of Baselines Used with Corn Starch Ethanol and Corn Stove Ethanol, Respectively

In 2040, all the E set fuels in CA with corn starch ethanol show energy use reductions compared with baselines (see Figure 9-27), except for F14 in total energy use . F15 and F19 show the greatest reductions: over 13% for fossil energy use and about 18-20% for petroleum energy use. However, total energy use reductions for those fuels are less than 3% for all ON/CR ratios. With corn stover ethanol, these two fuels show the greatest fossil energy use reduction of about 17-18%, and the greatest petroleum energy use reduction of about 18-20%, but a total energy increase of over 10%. As in PADD 3, the impact of fuel economy changes (with varying ON/CR assumptions) on energy use reduction is small.

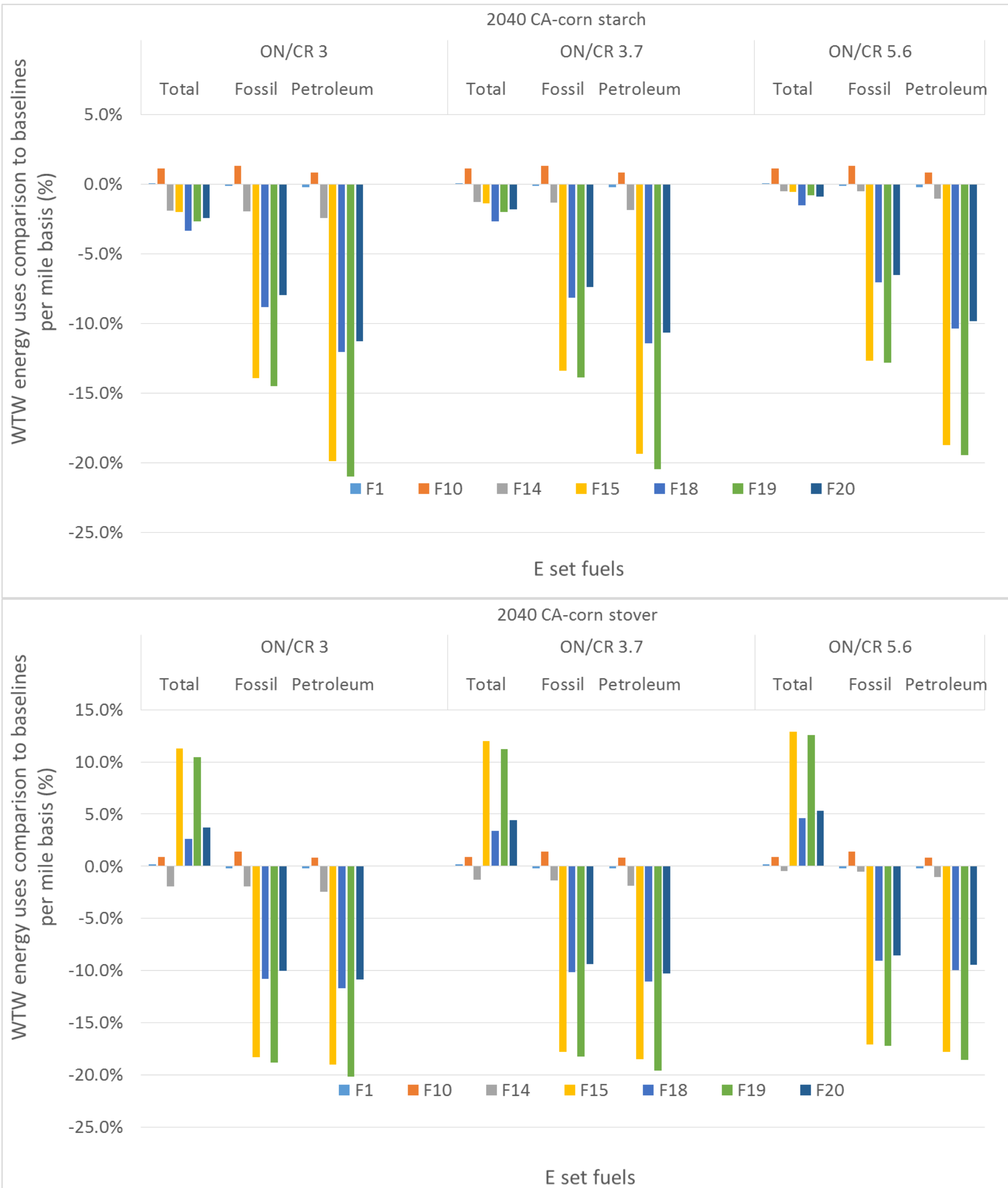


Figure 9-27. Per Mile Comparison of E Set Domestic Gasolines (with Corn Starch Ethanol and Corn Stover Ethanol) Energy Uses to Baselines in CA in 2040 (for ON/CR of 3.0, 3.7, and 5.6). Dual Sets of Baselines Used with Corn Starch Ethanol and Corn Stove Ethanol, Respectively

9.1.2.4 Aggregate Refinery E Set Fuels GHG Emissions Per Mile Driven

Fuel economy gains impact the GHG emissions per mile driven. E set fuels' WTW GHG emissions, based on various assumptions of fuel economy gains with high octane numbers (ON/CR of 3.0, 3.7, and 5.6) are summarized here. Following the guidance of AEO2018, from 2015 to 2022 a 20% fuel economy gain in MY passenger cars was applied for all cases (base cases and HOF cases), and from 2015 to 2040 a 22.4% fuel economy gain was applied for all cases (base cases and HOF cases). One could argue that HOF could be part of technology options to meet the increased fuel economy of MY vehicles as projected by AEO. One could then develop a base case where HOF is completely taken out for vehicle fuel economy gains as projected by AEO. The resultant net energy and GHG emission changes from this newly established base case and the AEO case that one believes that HOF was considered would be net benefits of HOF. Note that the pathways or fuels/engine combinations to achieve such fuel efficiency gains were not specified in AEO2018. As one can imagine, there are uncertainties: 1) whether the HOF strategy studied in the present work was one of the pathways enabling future fuel economy gain and therefore contributing to new fuel economy baseline foundation for year 2022 and 2040; and 2) how much the HOF technology option would contribute to the projected fuel economy gains.

Due to the lack of such information and understanding, the AEO projected fuel economy for year 2022 and 2040 are applied to baseline E10 fuels in base cases, and the fuel economies of HOF gasoline are estimated by comparing the fuel economy gains of HOF gasolines with baseline E10 gasolines for a given year. Such fuel economy gain assumptions influence the absolute fuel economy values and GHG emissions values of both baseline gasolines and HOF gasolines. This approach, however, does not affect the examination of the relative benefits of using HOF gasolines to baseline E10 gasoline, for a given year. Thus, the attention should be focused on the relative changes, not the absolute values, of energy use and GHG emissions of HOF results presented in this study.

WTW GHG emissions of E set BAU, HOF and domestic gasolines in 2022 in PADD 3, with corn starch ethanol and corn stover ethanol, were calculated on a per-mile basis and are shown in Figure 9-28 and Figure 29. Again, in 2022, only one baseline — with corn starch ethanol — is used for comparison.

The GHG emission patterns of E set gasolines on a per-mile basis are consistent with those on a per-MJ basis. As the GHG emissions at the PTW stage dominate the overall WTW GHG emissions, HOFs reduce GHG emissions significantly with bio-blending that dilutes the fossil carbon source. In the WTW analysis, the CO_2 formed from the combustion of ethanol is considered to be "biogenic" and is excluded from the PTW GHG calculations.

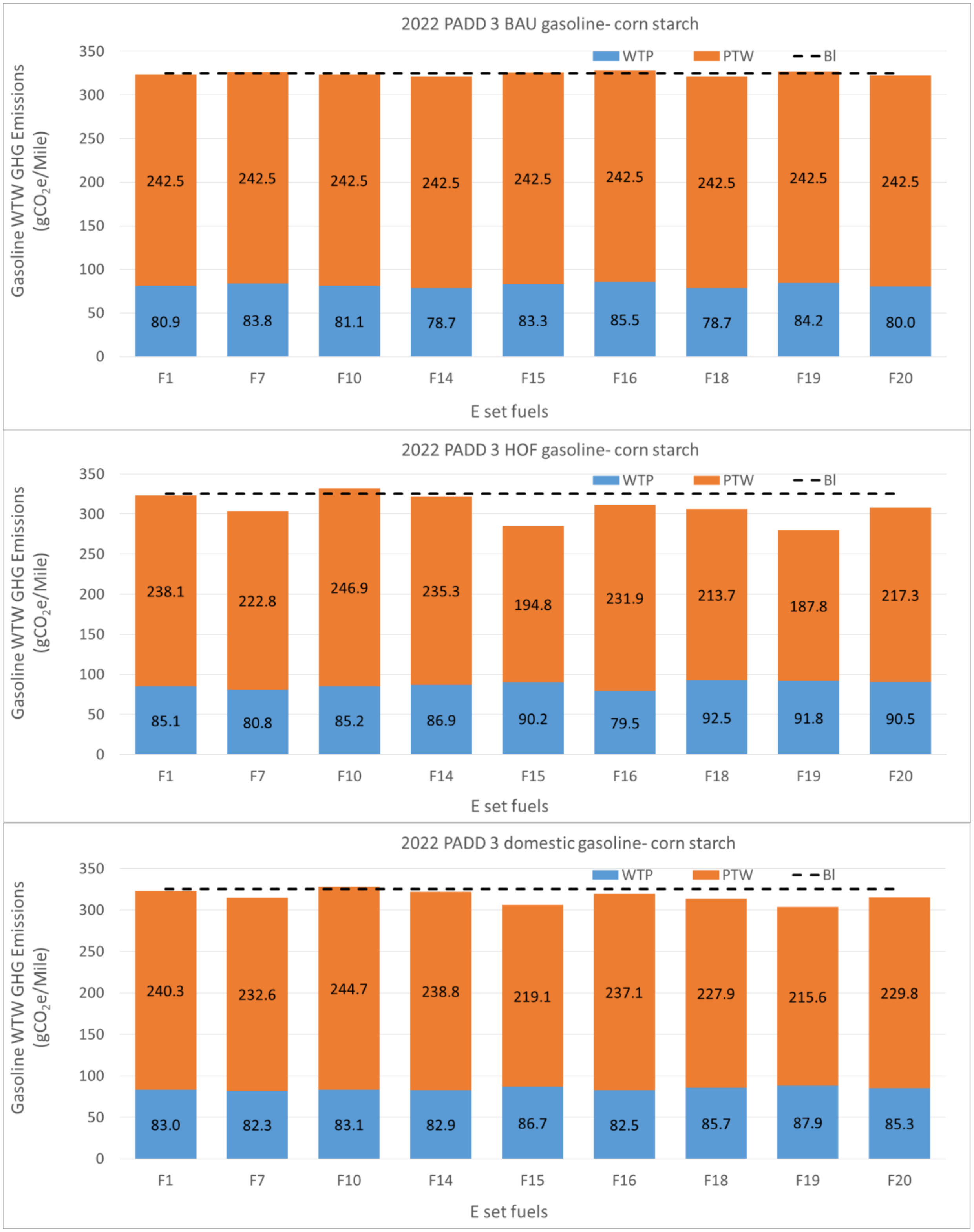


Figure 9-28. WTW GHG Emissions of E Set Finished Gasolines (BAU, HOF and Domestic Finished Gasoline) with Corn Starch Ethanol in PADD 3 in 2022, Per-Mile Basis (for ON/CR of 3.0). Baselines Use Corn Starch Ethanol

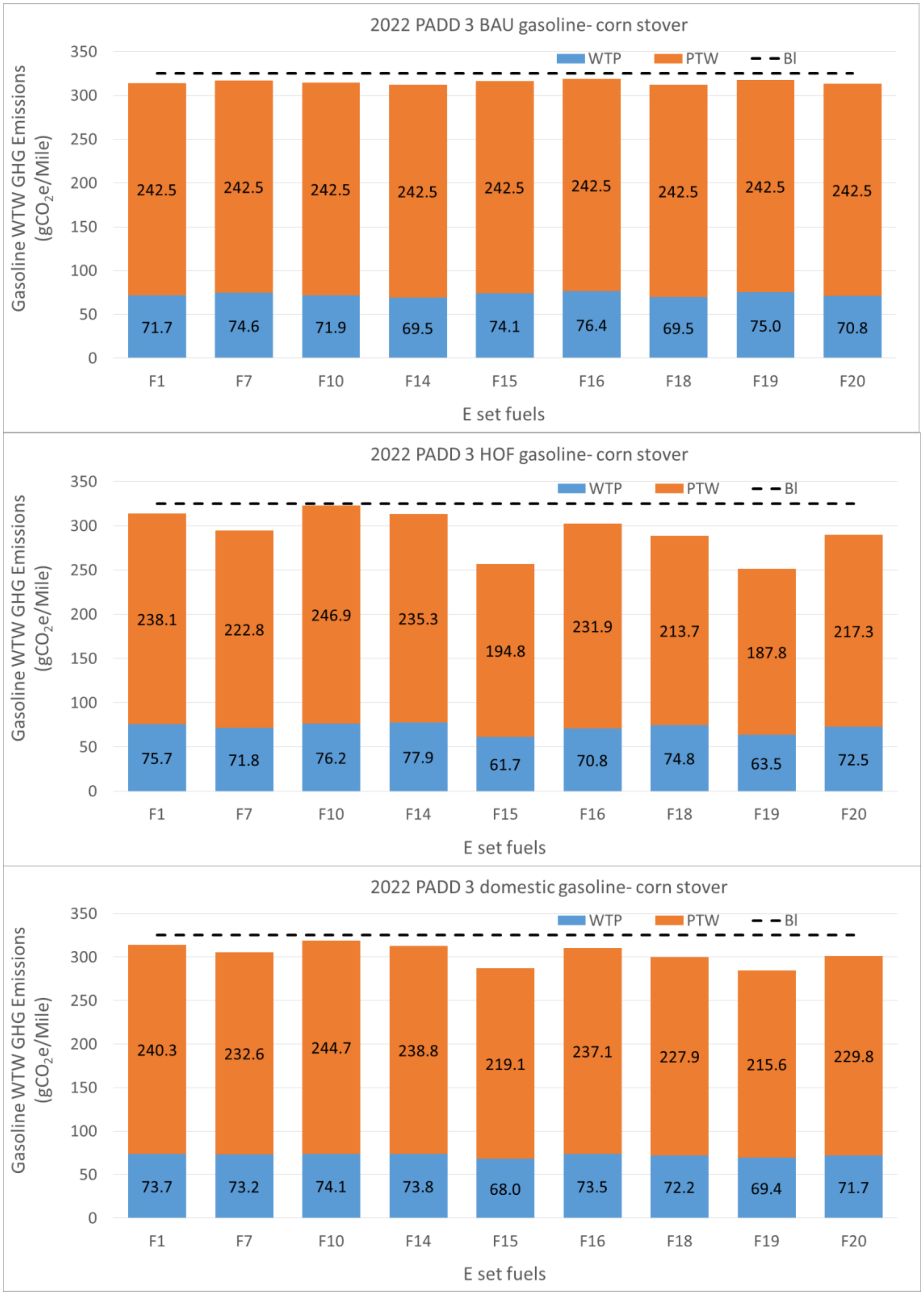


Figure 9-29. WTW GHG Emissions of E Set Finished Gasolines (BAU, HOF and Domestic) with Corn Stover Ethanol in PADD 3 in 2022, Per-Mile Basis (for ON/CR of 3.0). Baselines Use Corn Starch Ethanol

The GHG emissions of BAU and HOF gasolines with different fuel economies in PADD 3 in 2022 are summarized in Table 9-7 below.

Similarly, the breakdown of E set gasoline GHG emissions in CA in 2022 is shown in Figure 9-30 and Figure 9-31, for corn ethanol and corn stover ethanol, respectively.

Table 9-7. The WTW GHG Emissions of E Set BAU and HOF Finished Gasolines Produced in PADD 3 Refinery in 2022, with Ethanol from Corn Starch and Corn Stover, Respectively

PADD 3 2022	BAU Starch (g CO_2/mile)	HOF Starch (g CO_2/mile)		
ON/CR	10.5 CR	3 ON/CR	3.7 ON/CR	5.6 ON/CR
F1	323.4	323.2	323.2	323.2
F7	326.2	303.6	305.8	309.3
F10	323.6	332.1	332.1	332.1
F14	321.2	322.2	324.2	326.8
F15	325.7	285.1	286.9	289.2
F16	328.0	311.5	313.6	317.4
F18	321.2	306.2	308.3	312.1
F19	326.7	279.6	281.6	285.0
F20	322.5	307.8	309.9	312.7
PADD 3 2022	**BAU Stover (g CO_2/mile)**	**HOF Stover (g CO_2/mile)**		
ON/CR	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR
F1	314.2	314.0	314.0	314.0
F7	317.0	305.7	306.8	308.6
F10	314.4	318.8	318.8	318.8
F14	312.0	312.6	313.6	314.9
F15	316.5	287.1	288.0	289.2
F16	318.8	310.6	311.7	313.6
F18	312.0	300.1	301.2	303.0
F19	317.5	284.9	285.9	287.6
F20	313.3	301.5	302.5	303.9

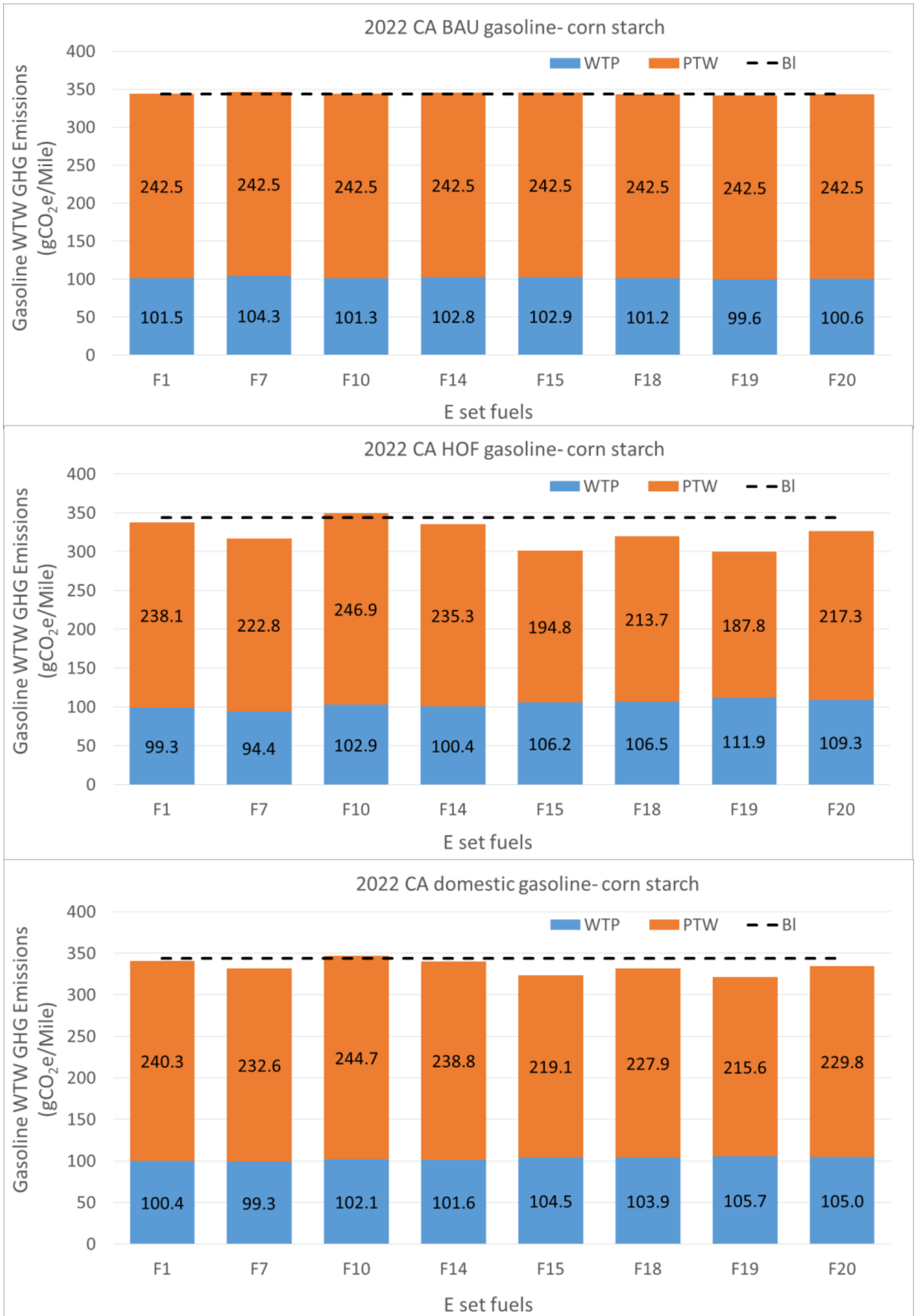


Figure 9-30. WTW GHG Emissions of E Set Finished Gasolines (BAU, HOF and Domestic) with Corn Starch Ethanol in CA in 2022, Per-Mile Basis (for ON/CR of 3.0).Baselines Use Corn Starch Ethanol

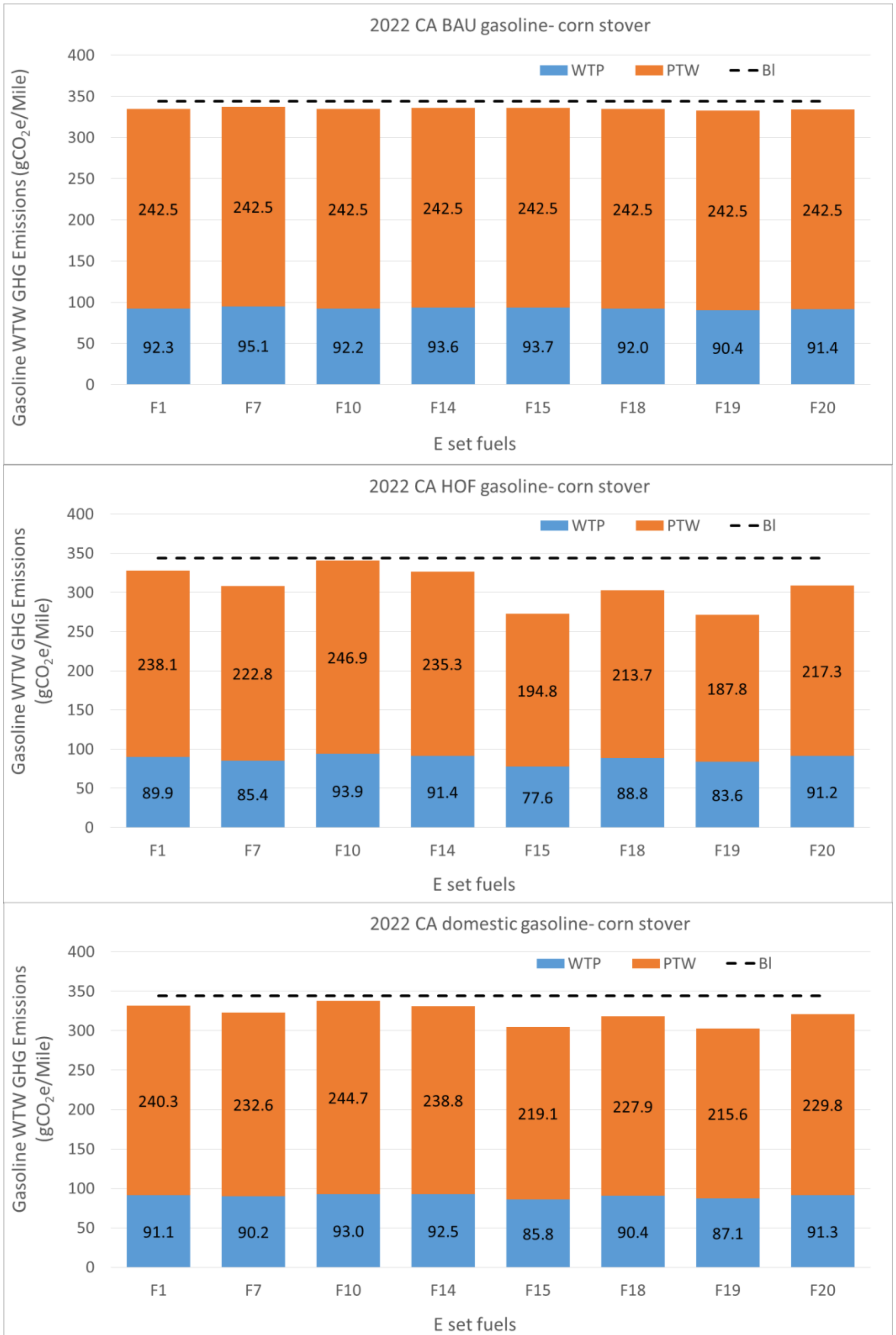


Figure 9-31. WTW GHG Emissions of E Set Finished Gasolines (BAU, HOF and Domestic) with Corn Stover Ethanol in CA in 2022, Per-Mile Basis (for ON/CR of 3.0). Baselines Use Corn Starch Ethanol.

The GHG emissions with 3.7 and 5.6 ON/CR assumptions show similar patterns, and while the breakdown figures are not shown here, the WTW results are listed in Table 9-8.

Table 9-8. WTW GHG Emissions of E Set BAU and HOF Finished Gasolines Produced in CA Refinery in 2022, with Ethanol from Corn Starch and Corn Stover, Respectively

CA 2022	BAU Starch (g CO_2/mile)	HOF Starch (g CO_2/mile)		
ON/CR	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR
F1	344	337.4	337.4	337.4
F7	346.7	317.2	319.5	323.2
F10	343.8	349.8	349.8	349.8
F14	345.3	335.7	337.8	340.6
F15	345.4	301	302.9	305.4
F18	343.7	320.2	322.4	326.3
F19	342.1	299.7	301.8	305.5
F20	343.1	326.6	328.7	331.7
CA2022	BAU Stover (g CO_2/mile)	HOF Stover (g CO_2/mile)		
ON/CR	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR
F1	334.8	328	328	328
F7	337.6	308.2	310.4	314
F10	334.6	340.8	340.8	340.8
F14	336.1	326.7	328.7	331.4
F15	336.2	272.5	274.2	276.4
F18	334.5	302.4	304.6	308.2
F19	332.9	271.4	273.4	276.7
F20	333.9	308.6	310.6	313.4

The breakdown of E set WTW GHG emissions in PADD 3 and CA in 2040 is shown in the Figure 9-32 and Figure 9-33, for ON/CR of 3.0.

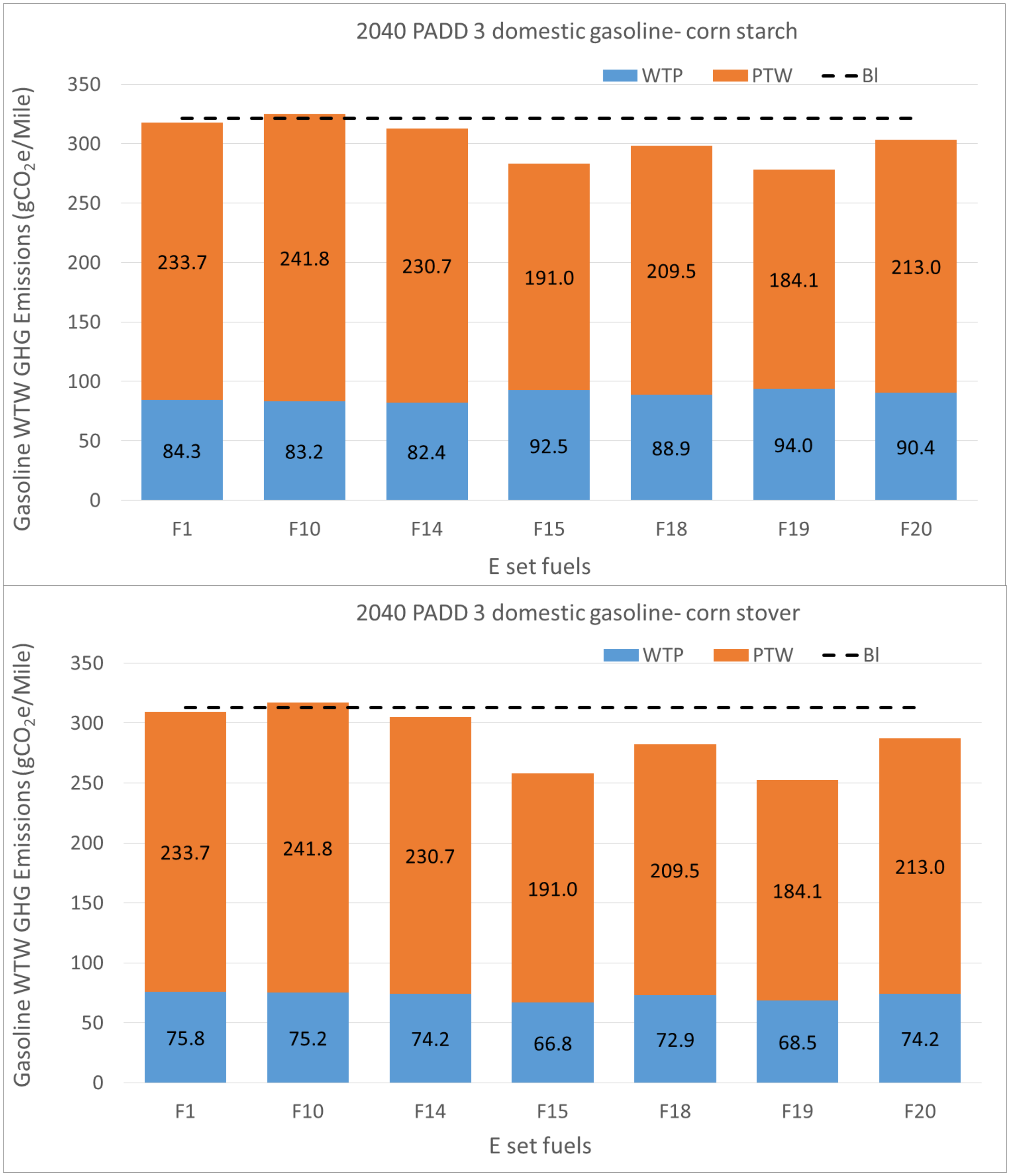


Figure 9-32. WTW GHG Emissions of E Set Domestic Finished Gasolines with Corn Starch and Corn Stover Ethanol, in PADD 3 in 2040, Per-Mile Basis (for ON/CR of 3.0). Dual Sets of Baselines Used with Corn Starch Ethanol and Corns Stove Ethanol, Respectively

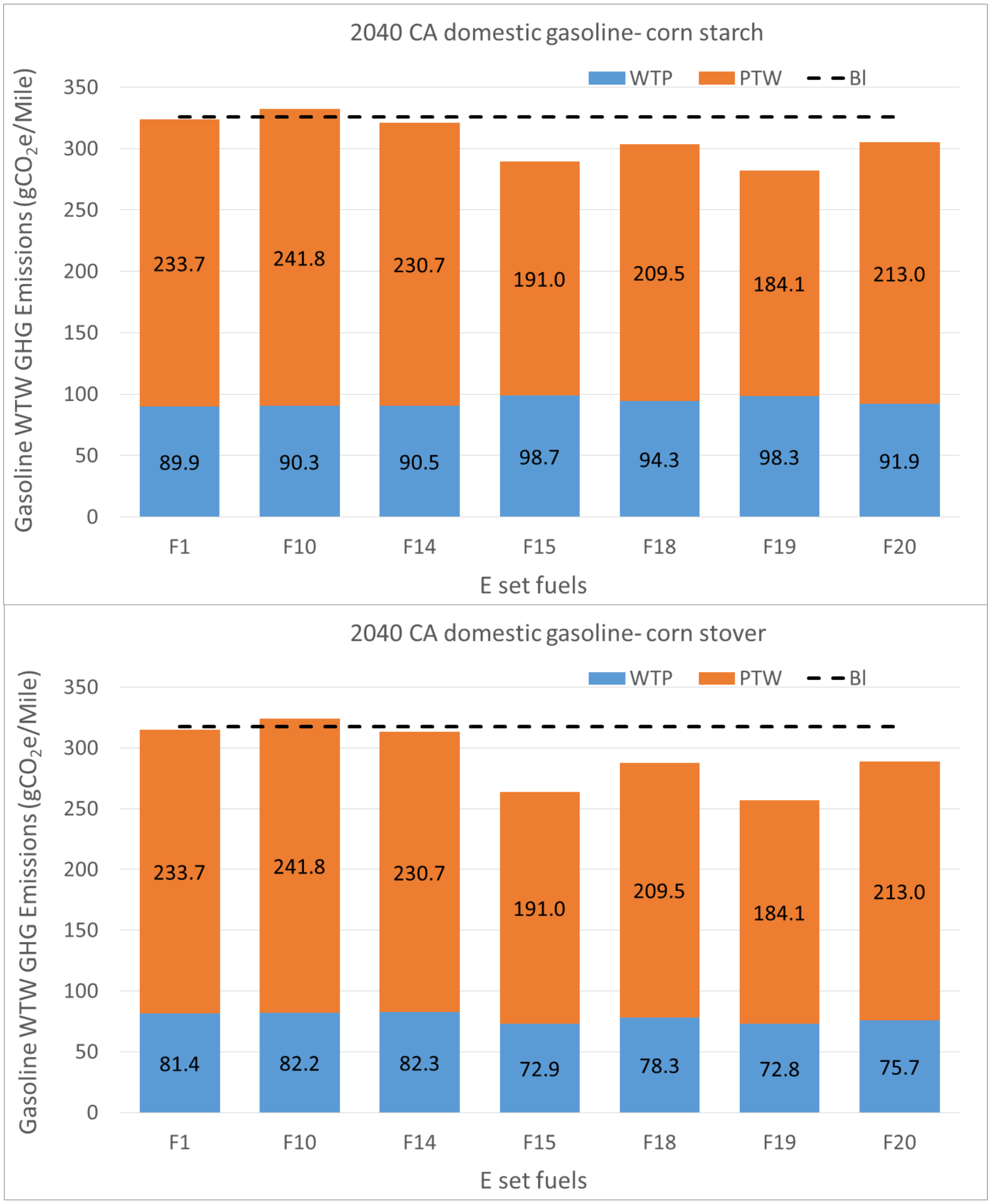


Figure 9-33. WTW GHG Emissions of E Set Domestic Finished Gasolines with Corn Starch and Corn Stover Ethanol, in CA in 2040, Per-Mile Basis (for ON/CR of 3.0). Dual Sets of Baselines Used with Corn Starch Ethanol and Corns Stove Ethanol, Respectively

In 2040, two sets of baselines are used: one with ethanol from corn starch and the other with ethanol from corn stover. For both PADD 3 and CA cases, all high-octane fuels show GHG emission reductions compared with baselines, given the same ethanol source. For E10 fuels with a RON of 91, Fuel 10 showed a slight increase in GHG emissions, owing to its higher than baseline carbon density. The overall WTW GHG emissions of domestic gasolines for all E set cases in aggregate refineries, with different fuel economies, are summarized in Table 9-9.

Table 9-9. PADD 3 2022 E Set Domestic Finished Gasolines WTW GHG Emissions (g/mile) with Ethanol from Corn Starch and Corn Stover, Respectively

2022 PADD 3	Corn Starch			Corn Stover		
	3 ON/CR	3.7 ON/CR	5.6 ON/CR	3 ON/CR	3.7 ON/CR	5.6 ON/CR
F1	323.3	323.3	323.3	314.0	314.0	314.0
F7	314.8	316	317.8	305.7	306.8	308.6
F10	327.8	327.8	327.8	318.8	318.8	318.8
F14	321.7	322.7	324	312.6	313.6	314.9
F15	305.8	306.8	308	287.1	288.0	289.2
F16	319.5	320.7	322.6	310.6	311.7	313.6
F18	313.6	314.7	316.6	300.1	301.2	303.0
F19	303.5	304.6	306.4	284.9	285.9	287.6
F20	315.1	316.2	317.6	301.5	302.5	303.9
2022 CA	Corn Starch			Corn Stover		
F1	340.7	340.7	340.7	331.4	331.4	331.4
F7	331.9	333.1	335.0	322.8	323.9	325.8
F10	346.8	346.8	346.8	337.7	337.7	337.7
F14	340.4	341.5	342.9	331.3	332.4	333.7
F15	323.7	324.6	325.9	305.0	305.9	307.1
F18	331.8	333.0	335.0	318.3	319.4	321.4
F19	321.2	322.3	324.3	302.6	303.7	305.5
F20	334.8	335.9	337.4	321.2	322.2	323.7
2040 PADD 3	Corn Starch			Corn Stover		
F1	317.9	317.9	317.9	309.4	309.4	309.4
F10	325.1	325.1	325.1	317.0	317.0	317.0
F14	313.0	315.0	317.6	304.9	306.8	309.3
F15	283.5	285.3	287.7	257.8	259.4	261.5
F18	298.3	300.4	304.1	282.4	284.3	287.8
F19	278.1	280.1	283.5	252.6	254.4	257.5
F20	303.5	305.5	308.3	287.2	289.1	291.8
2040 CA	Corn Starch			Corn Stover		
F1	323.5	323.5	323.5	315.1	315.1	315.1
F10	332.1	332.1	332.1	324	324	324
F14	321.1	323.1	325.8	313	314.9	317.5
F15	289.7	291.5	293.9	263.9	265.6	267.8
F18	303.8	305.9	309.6	287.8	289.8	293.3
F19	282.4	284.4	287.9	256.9	258.7	261.9
F20	304.9	307.0	309.8	288.7	290.6	293.3

A comparison of E set fuel WTW GHG emissions to baselines is shown in the Figures 9-34 and Figure 9-35 below.

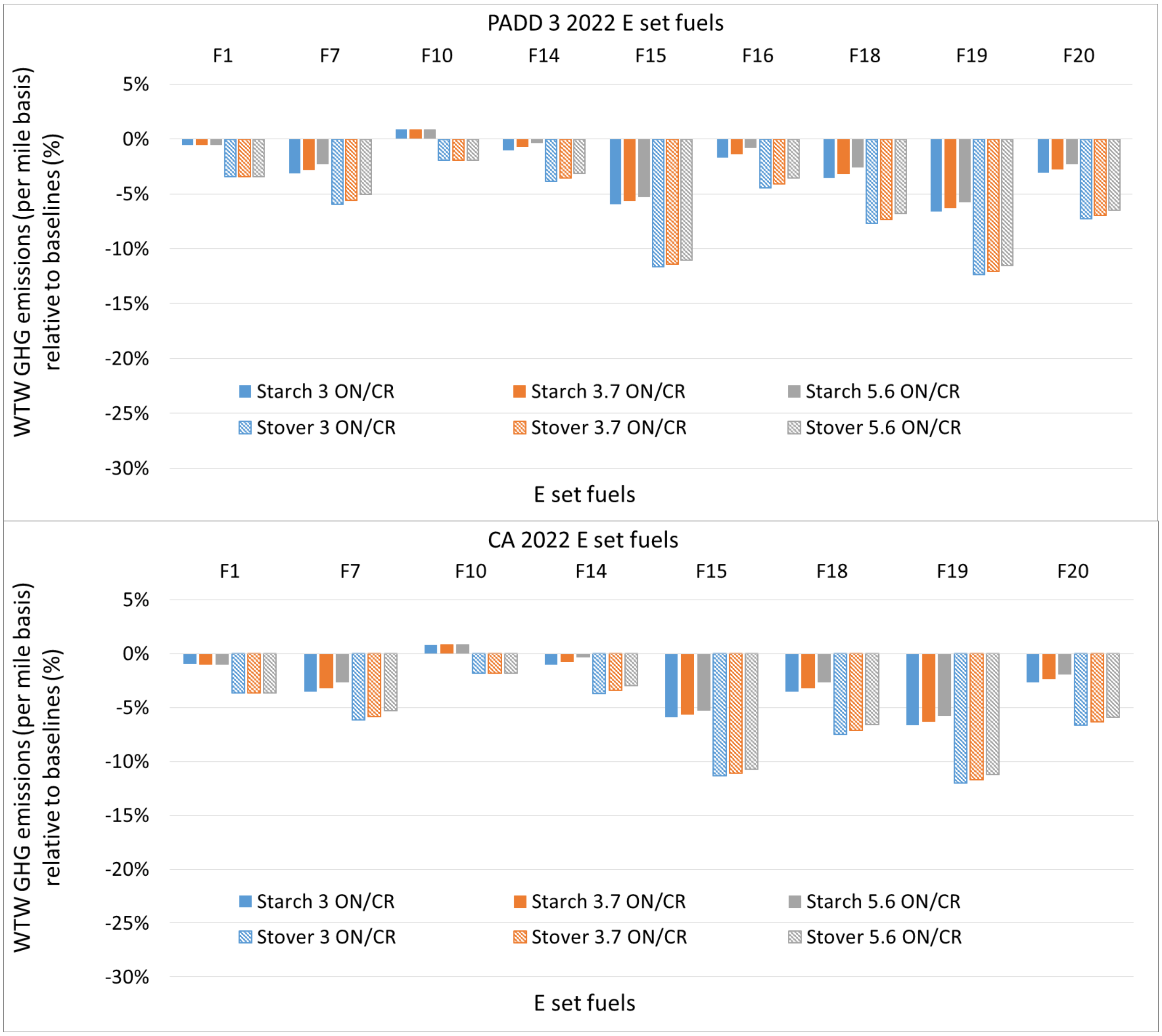


Figure 9-34. The E Set Fuels (Domestic Finished Gasolines) WTW GHG Emissions Compared to Baselinesin 2022 (per mile). Baselines Use Corn Starch Ethanol

In 2022, the base case uses ethanol from corn starch. All the E set fuels with either corn starch ethanol or corn stover ethanol are compared with the same set of baselines with corn starch ethanol. Compared with the baseline, the E set fuels with corn stover ethanol had greater WTW GHG emission reductions than those with corn starch ethanol. Compared with the base case, F1 fuels show a slight reduction in GHG emissions (owing to the fuel’s lower carbon content per unit energy), and Fuel 10 shows higher GHG emissions (owing to the fuel’s higher LHV). With a high RON of 100, Fuel 7 and Fuel 16 (both high RON E10 fuels) show noticeable GHG reductions compared with the baseline (E10 with 91 RON) in PADD 3. However, the refinery production of both F7 and F16 is quite challenging, leading to infeasible solutions in CA in 2022. The GHG reductions are especially pronounced for fuels with higher ethanol blending levels, with the highest reductions of about 10%–12% for E30 F15 and F19.

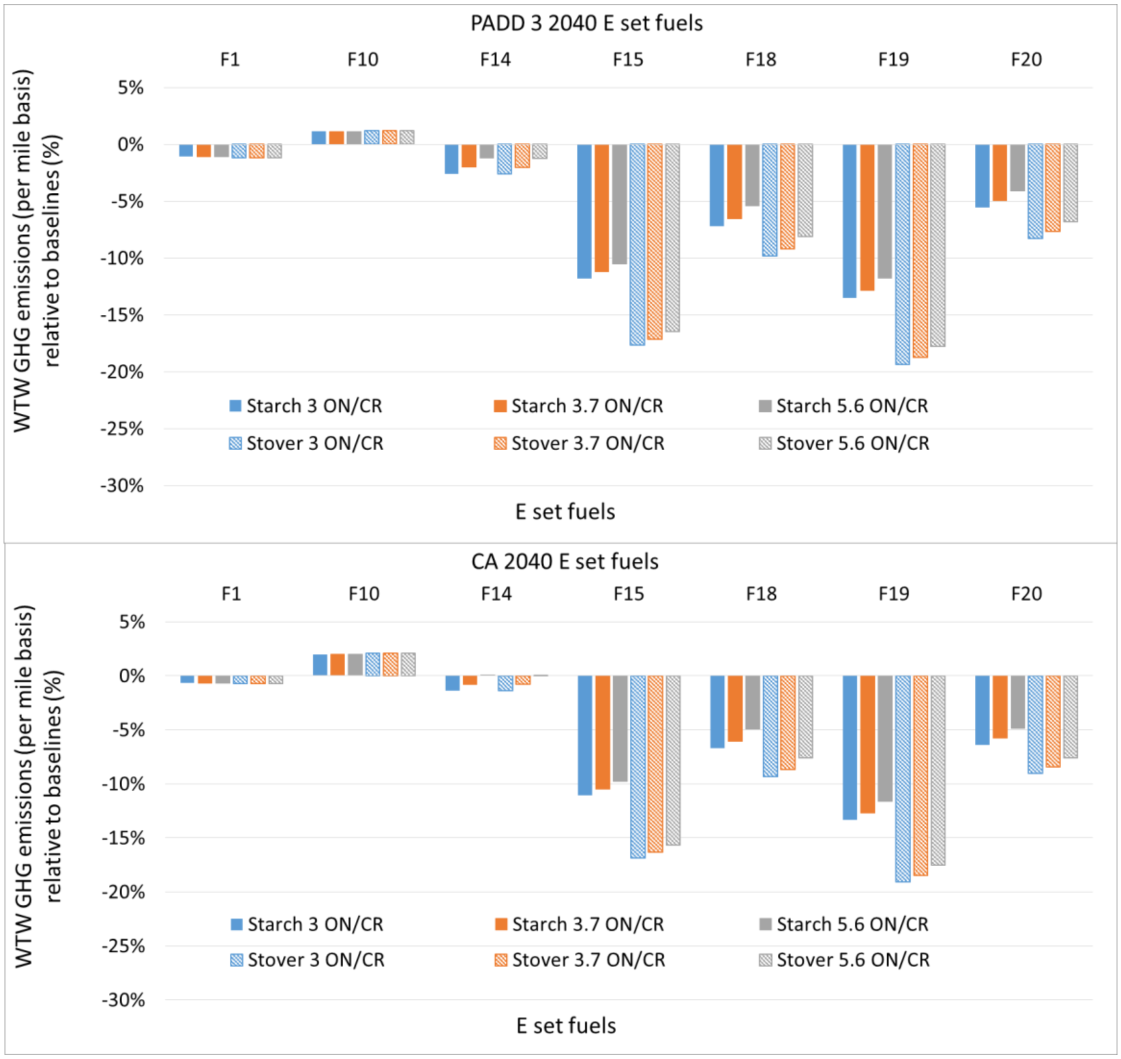


Figure 9-35. E Set Fuels (Domestic Finished Gasolines) WTW GHG Emission Changes Compared to Baselines in 2040 (per mile). Dual Sets of Baselines Used with Corn Starch Ethanol and Corns Stove Ethanol, Respectively

In 2040, except for F10, all the E set fuels show greater GHG reduction benefits. F1 and F14 show marginal reductions. With the challenge of producing 100% HOF in 2040, the LP modeling of Fuel 7 and Fuel 16 in PADD 3 and CA refineries did not yield feasible solutions (without additional investment). In 2040, E20 (F18 and F20) and E30 (F15 and F19) fuels show greater GHG reductions compared with baselines than in 2022, reaching about 17-18% for Fuel 15 and Fuel 19 with ethanol from corn stover.

9.1.3 WTW Analysis of Configuration Refineries Base Cases

9.1.3.1 Configuration Base Cases WTW Energy Use and GHG Emissions Per MJ of Fuel Used

The WTW energy use of E set fuels produced in various configuration refineries in different years is shown in Figure 9-36 for corn starch ethanol and corn stover ethanol.

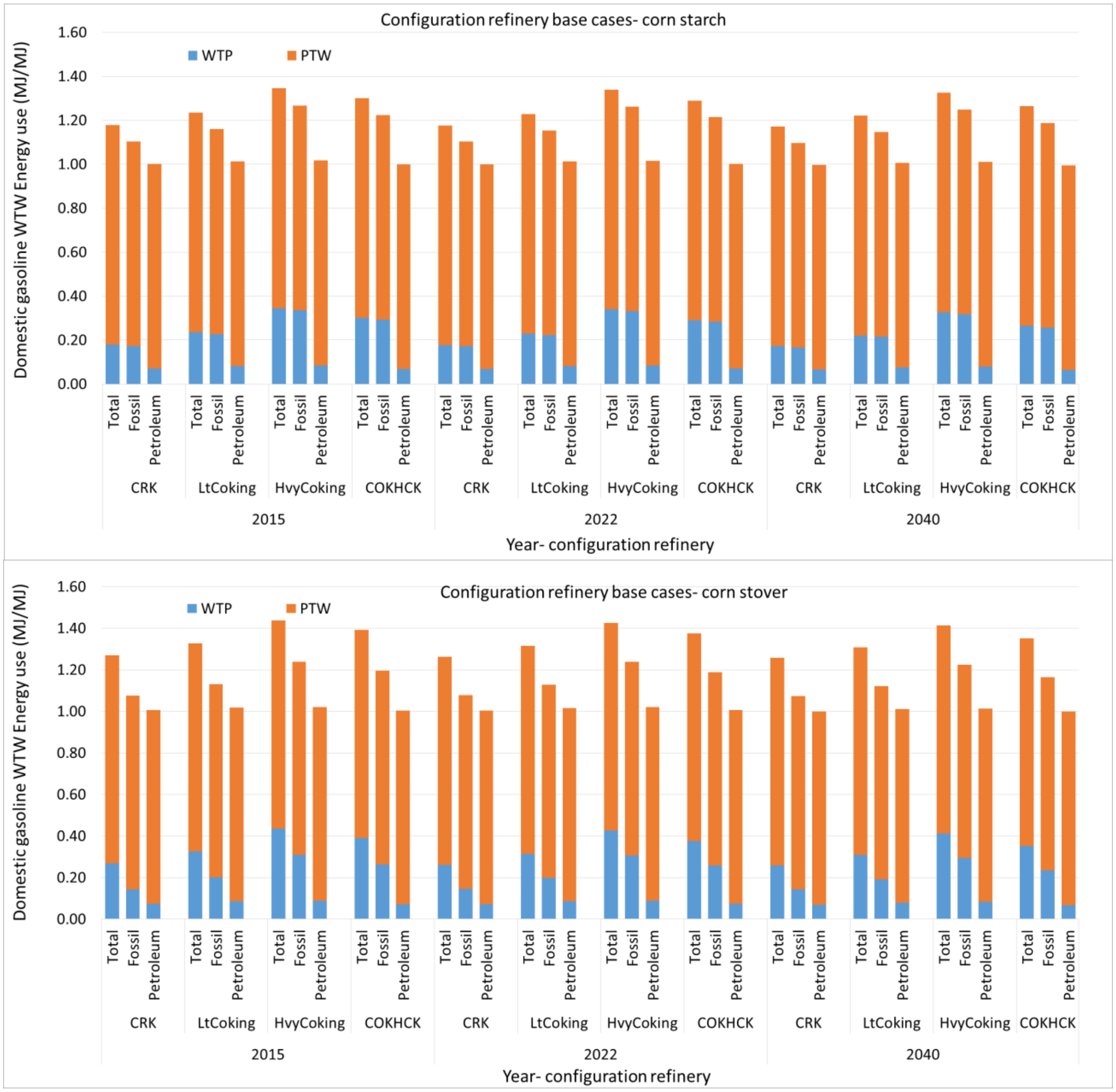


Figure 9-36. Configuration Base Cases Domestic Finished Gasoline WTW Energy Use with Corn Starch Ethanol and Corn Stover Ethanol, Respectively

For each year studied, the WTW total energy use for the base case E10 domestic gasoline pools increase in the order of CRK < LtCOK < COKHCK<HvyCOK <, due to differences in the WTP stage energy use. As discussed in Section 7, the WTP energy use of gasoline BOBs increases with refinery complexity, resulting in increasing refinery operation energy use. The energy use shown in Figure 9-35 is broken down by petroleum energy, NGC and renewable energy.

Comparison of the E set fuels energy use with ethanol from corn stover with that with ethanol from corn starch shows the former has higher renewable energy use, but lower natural gas and coal energy use. The petroleum energy use in both cases is quite similar.

Natural gas/coal energy use increases with increasing refinery complexity, in the order of CRK < LtCOK < COKHCK < HvyCOK. It is worth mentioning that at the refinery stage, HvyCOK has less natural gas and coal energy use than COKHCK does, with lower hydrogen demand. However, HvyCOK has higher energy use in crude recovery stage due to the use of energy-intensive oil sands.

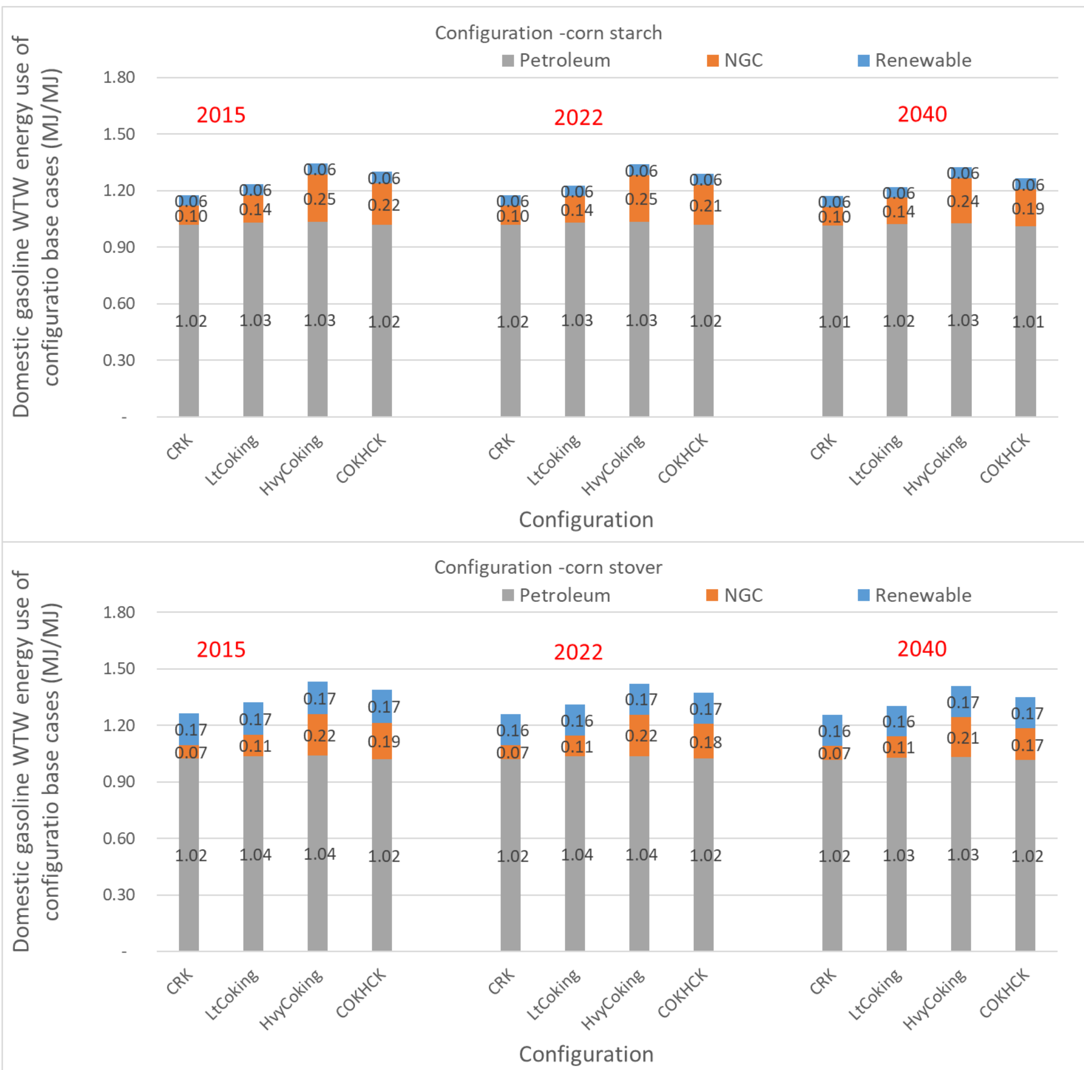


Figure 9-37. WTW Energy Uses of Base Case E10 Domestic Finished Gasolines Produced in Four Configuration Refineries

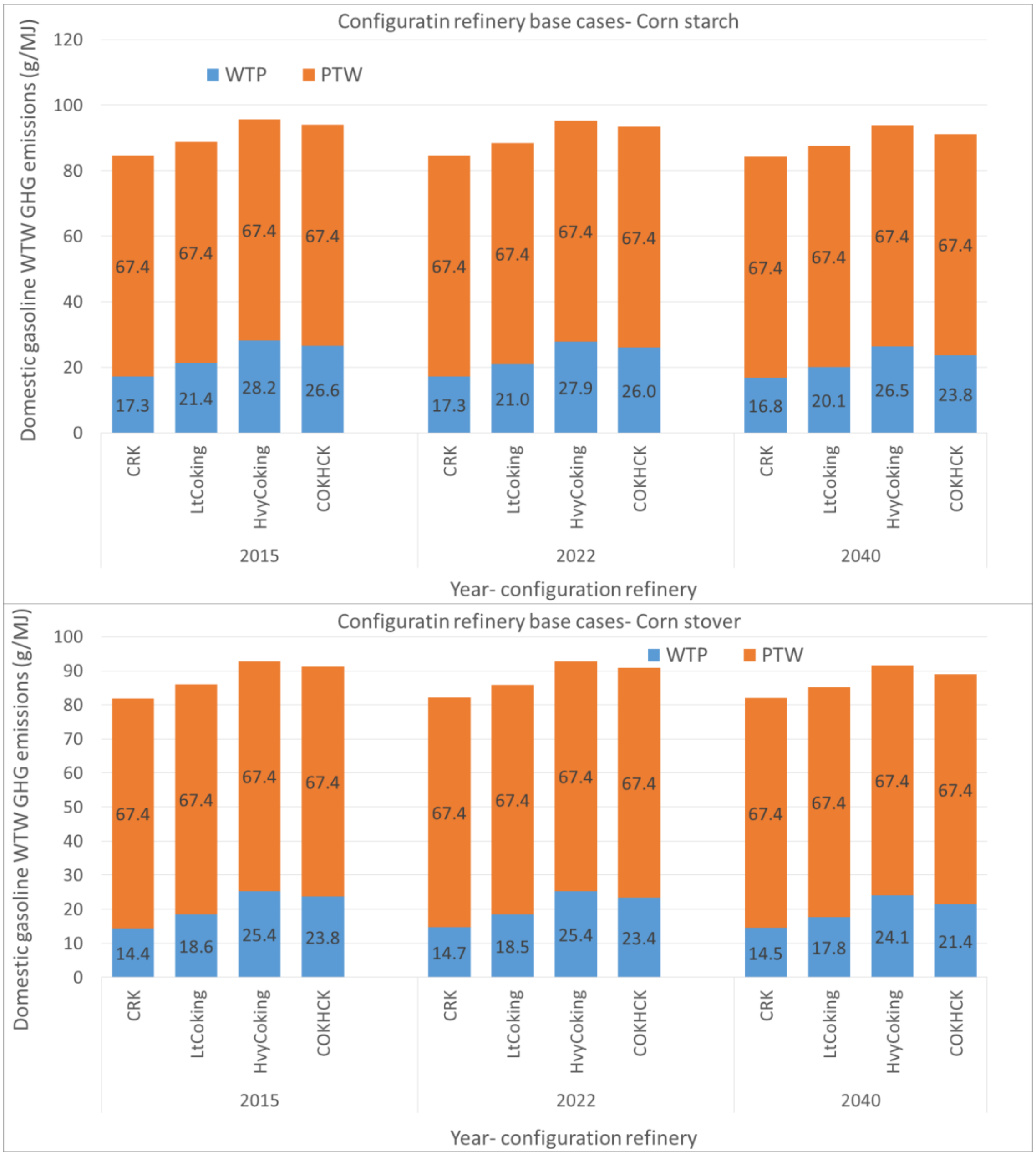


Figure 9-38. The Configuration Base Cases Domestic Finished Gasolines WTW GHG Emissions with Corn Starch Ethanol and Corn Stover Ethanol

Consistent with the trends of energy use, the gasoline GHG emissions of configuration refinery base cases increase with increasing refinery complexity. With 10% ethanol blending in the base cases, domestic gasoline with corn starch ethanol emits more GHG than that with corn stover ethanol by 2-3 g/MJ, about 2-3% of total WTW GHG emissions.

9.1.3.2 Configuration Base Cases WTW Energy Use and GHG Emissions Per Mile Driven

The WTW energy use on a per mile basis (MJ/mile) for the baseline fuels produced in configuration refineries in various years are shown in Figure 9-39. The results are also listed in Appendix 4 in Table A4-13 for details.

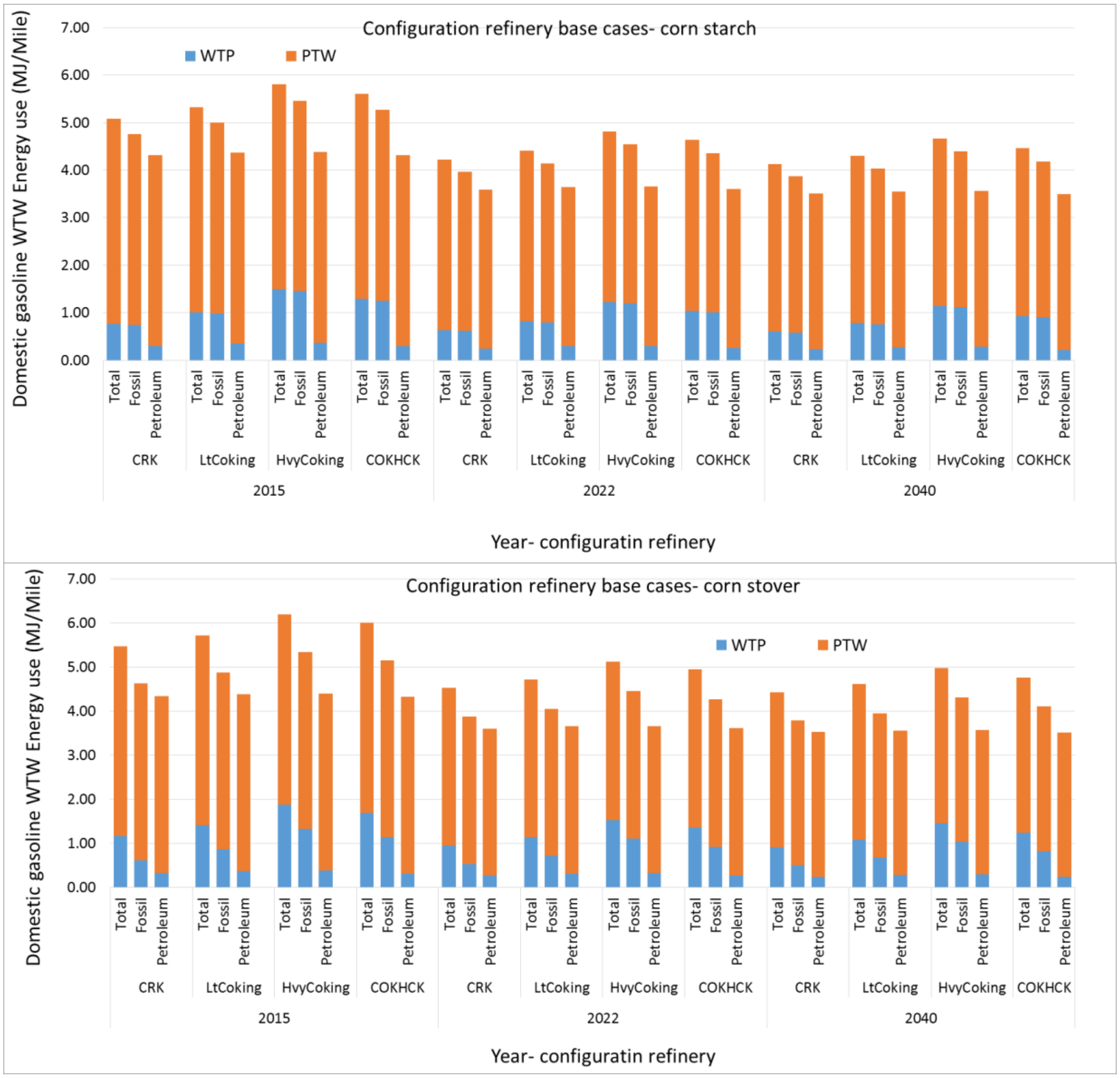


Figure 9-39. Configuration Refinery Base Cases E Set Domestic Finished Gasoline s WTW Energy Uses (MJ/mile) with Corn Starch Ethanol and Corn Stover Ethanol

GHG emissions per mile are shown in Figure 9-40. As expected, the GHG emissions increase in the order of CRK < LtCOK < COKHCK < HvyCOK. For each configuration case, the energy use decreases from 2015 to 2022 and from 2022 to 2040, due to the sizeable fuel economy gains from 2015 to 2022 and from 2022 to 2040. As with energy use per MJ, fuels with corn stover ethanol use more total energy but less fossil energy and petroleum energy than fuels with corn starch ethanol.

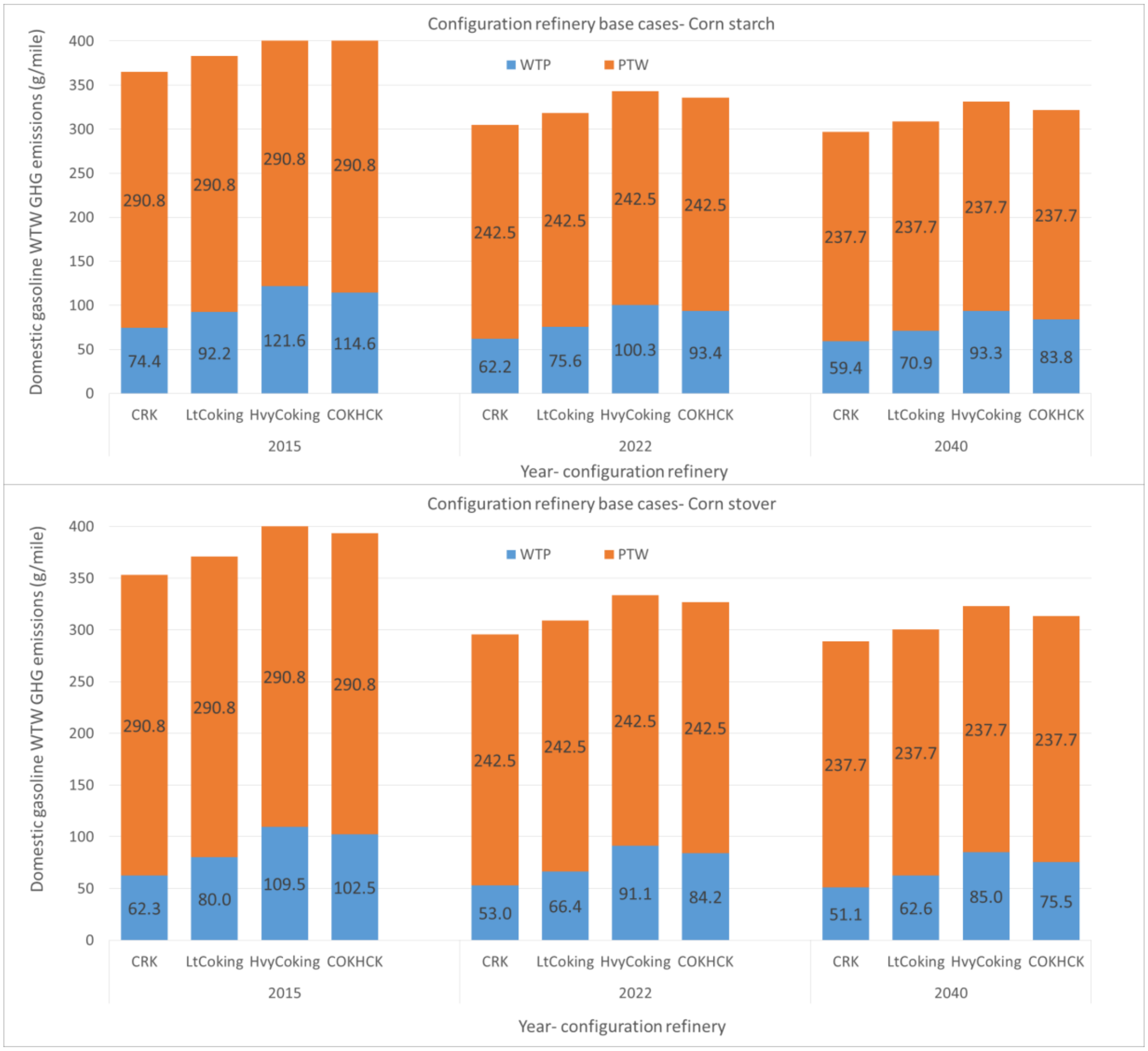


Figure 9-40. Configuration Refinery Base Cases Domestic Finished Gasolines (E10) WTW GHG Emissions (MJ/mile) (for ON/CR of 3.0) with Corn Starch Ethanol and Corn Stover Ethanol

9.1.4 WTW Analysis of E Set Fuels Produced in Configuration Refineries

9.1.4.1 Configuration E Set Fuels WTW Energy Use and GHG Emissions Per MJ of Fuel Used

Energy use for E set BAU and HOF fuels produced in configuration refineries in 2022 is shown in Table 9-10.

Table 9-10. WTW Energy Uses of E Set BAU and HOF Finished Gasolines in Configuration Refineries in 2022

		BAU (MJ/MJ) Corn Starch			HOF (MJ/MJ) Corn Starch		
Configuration	Fuel	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
CRK	F10	1.17	1.12	1.02	1.17	1.12	1.02
	F14	1.16	1.10	1.01	1.19	1.13	1.03
	F18	1.15	1.10	1.00	1.22	1.07	0.94
	F19	1.16	1.11	1.01	1.24	1.06	0.90
	F20	1.17	1.11	1.01	1.21	1.06	0.93
LtCOK	F10	1.23	1.18	1.03	1.22	1.16	1.03
	F14	1.21	1.15	1.02	1.24	1.18	1.04
	F18	1.20	1.15	1.01	1.27	1.13	0.95
	F19	1.22	1.16	1.02	1.28	1.10	0.91
	F20	1.21	1.16	1.02	1.26	1.12	0.95
HvyCOK	F10	1.34	1.28	1.03	1.34	1.28	1.03
	F14	1.32	1.26	1.02	1.36	1.30	1.05
	F18	1.32	1.26	1.02	1.38	1.23	0.95
	F19	1.32	1.26	1.02	1.38	1.20	0.92
	F20	1.31	1.25	1.02	1.38	1.23	0.96
COKHCK	F10	1.29	1.23	1.02	1.29	1.23	1.02
	F18	1.28	1.22	1.01	1.30	1.16	0.94
	F19	1.29	1.23	1.02	1.31	1.13	0.89
	F20	1.27	1.21	1.02	1.29	1.14	0.92
CRK	F10	1.26	1.09	1.02	1.26	1.09	1.02
	F14	1.24	1.08	1.01	1.27	1.10	1.03
	F18	1.24	1.07	1.01	1.39	1.02	0.95
	F19	1.25	1.08	1.01	1.51	0.98	0.91
	F20	1.25	1.09	1.01	1.38	1.01	0.94
LtCOK	F10	1.32	1.15	1.04	1.30	1.14	1.03
	F14	1.29	1.13	1.02	1.32	1.16	1.05
	F18	1.29	1.12	1.02	1.45	1.08	0.96
	F19	1.30	1.14	1.03	1.55	1.02	0.92
	F20	1.30	1.13	1.02	1.44	1.06	0.95

Table 9-10. (Cont.)

		BAU (MJ/MJ) Corn Stover			HOF (MJ/MJ) Corn Stover		
Configuration	Fuel	Total Energy	Fossil	Petroleum	Total Energy	Fossil	Petroleum
HvyCOK	F10	1.42	1.25	1.04	1.42	1.26	1.03
	F14	1.40	1.24	1.02	1.44	1.27	1.05
	F18	1.40	1.24	1.03	1.56	1.18	0.96
	F19	1.40	1.23	1.03	1.65	1.12	0.93
	F20	1.39	1.23	1.03	1.55	1.18	0.96
COKHCK	F10	1.37	1.21	1.03	1.37	1.20	1.03
	F18	1.36	1.19	1.02	1.48	1.10	0.95
	F19	1.37	1.20	1.02	1.58	1.05	0.90
	F20	1.36	1.19	1.03	1.47	1.09	0.93

As was observed in the aggregate refinery cases, for each E set fuel, the energy use for BAU gasoline is similar to that of baselines, while the energy use for HOF gasolines varies with the ethanol blending level.

The E set domestic gasoline energy use, the combined energy use of BAU and HOF gasolines, is shown in Figures 9-41 for corn starch ethanol and 9-42 for corn stover ethanol.

E set domestic gasoline energy use increases with increasing refinery complexity in the WTP stage, which was discussed in detail in Section 7. The WTW energy use of E set gasoline with corn starch ethanol has lower total energy use, but higher fossil energy and petroleum energy use, than gasoline with corn stover ethanol. The overall energy use values are summarized in Appendix 4 in Table A4-14.

Energy use for E set domestic gasoline, with both corn starch ethanol and corn stover ethanol, are shown in Figure 9-41 and Figure 9-42. The values are compared with baselines on the per-MJ basis, shown in Figures 9-43 and 9-44.

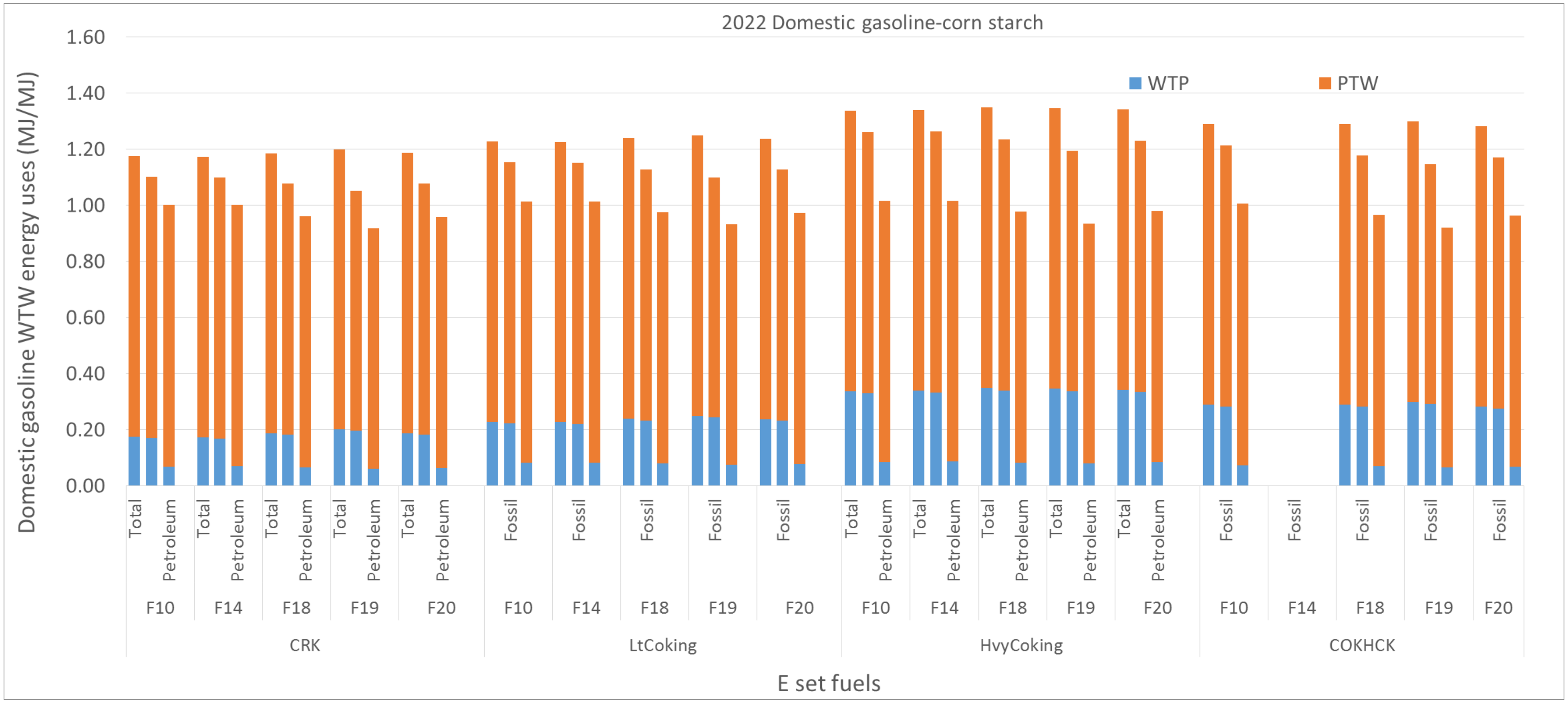


Figure 9-41. WTW Energy Use of E Set Fuels (Domestic Finished Gasolines) with Corn Starch Ethanol Produced in Configuration Refineries in 2022, Broken Down by WTP and PTW stages

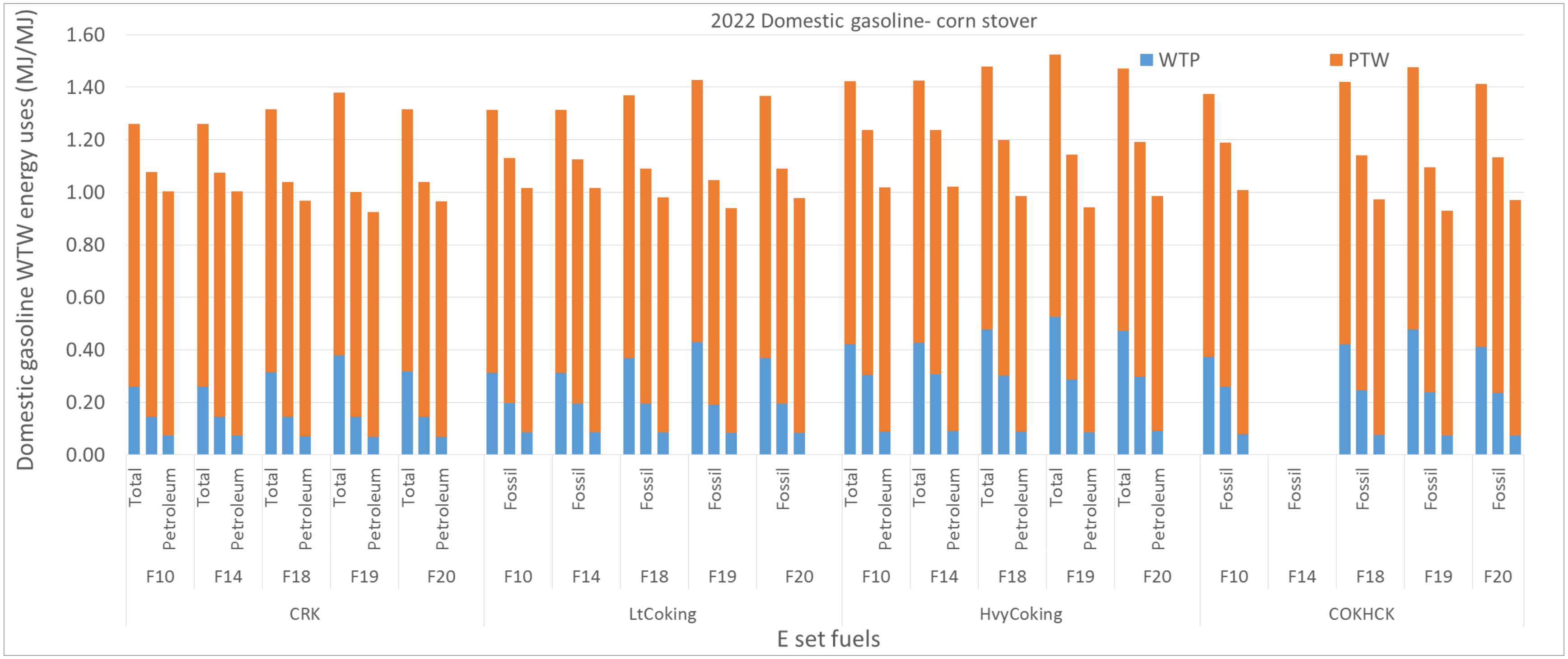


Figure 9-42. WTW Energy Use of E Set Fuels (Domestic Finished Gasolines) with Corn Stover Ethanol Produced in Configuration Refineries in 2022, Broken Down by WTP and PTW Stages

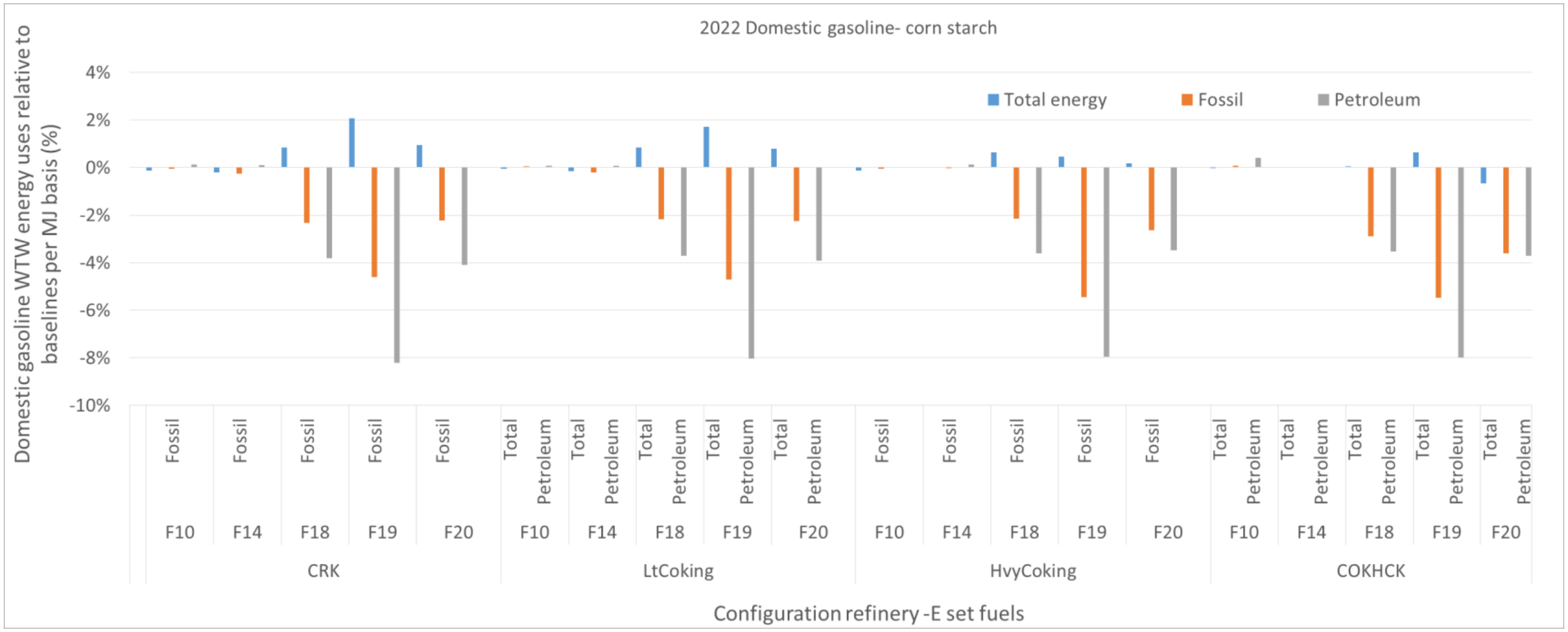


Figure 9-43. Changes of Energy Uses of E Set Domestic Finished Gasoline (with Corn Starch Ethanol) Relative to That of Baselines in 2022, per MJ Basis. Baselines Use Corn Starch Ethanol

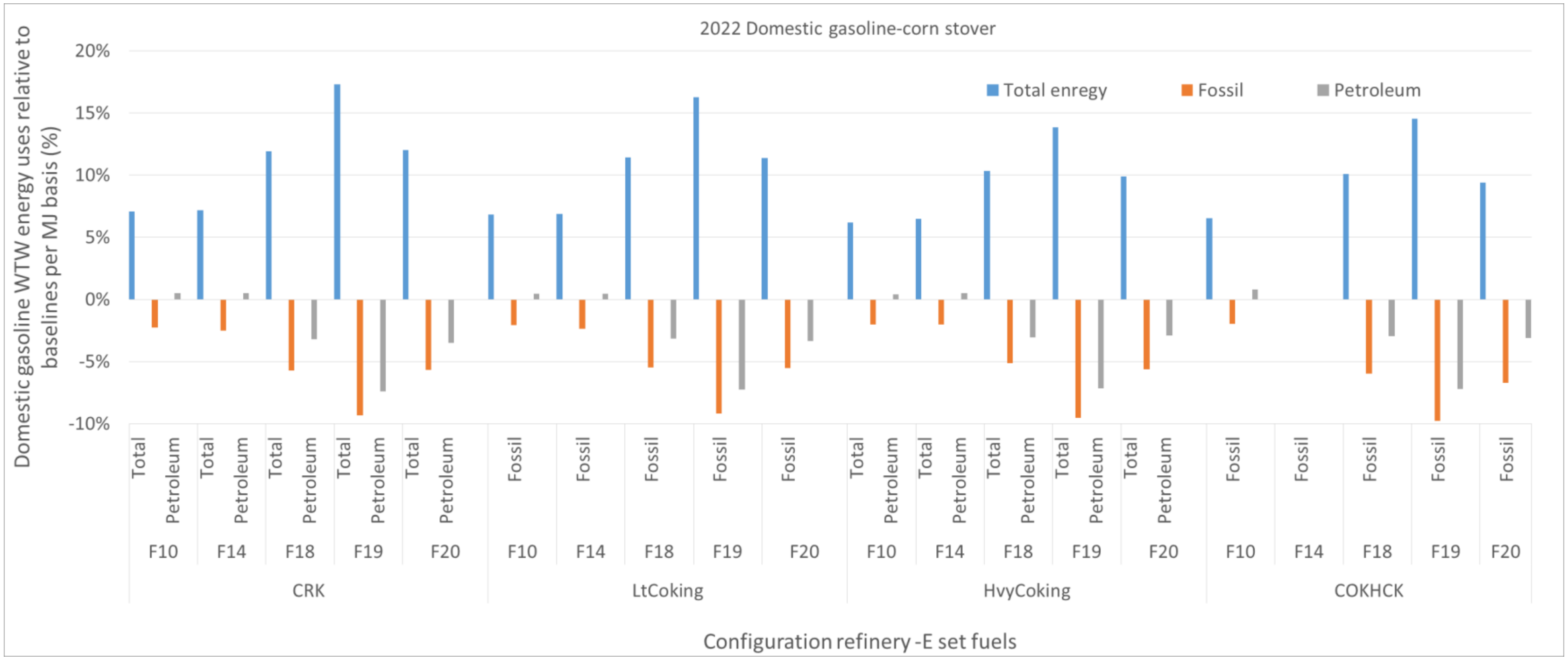


Figure 9-44. Changes of Energy Use for E Set Domestic Finished Gasoline (with Corn Stover Ethanol) to Baselines in 2022, per MJ Basis. Baselines Use Corn Starch Ethanol

In 2022, only corn starch ethanol is used in baselines. For E set domestic gasolines with corn starch ethanol, for all configuration refineries, energy use for E10 fuels F10 and F14 is similar to baseline. The high-octane-level ethanol blending fuels (F18, F19, and F20) use less fossil and petroleum energy than baselines (4%–8% less), but more total energy. All the E set domestic gasolines with corn stover ethanol show noticeably higher total energy use (7%–17% higher), but lower fossil energy use (2%–10% lower), than baselines, and similar or less petroleum energy use.

The energy use of E set gasolines in 2040, broken down by WTP and PTW, is shown in Figures 9-45 and 9-46. The results are also shown in Appendix 4 in Table A4-15 for details. For each fuel, energy use (total, fossil and petroleum) increases with increasing refinery complexity. For each configuration refinery, with increasing ethanol blending levels, the total energy use increases but the fossil energy use decreases. For any given fuel, relative to the domestic fuel pools produced in 2022 where only 50% of the pool is HOF, the fossil energy use in 2040 only decreases by about 1%–4%, despite the fact that in 2040 100% of the pool is HOF. Fuels with corn stover ethanol and with corn starch ethanol have similar petroleum energy use, but different fossil energy use. This observation is consistent with previous observations in the PADD cases. As with the configuration base cases, the corn starch ethanol cases have higher NGC/petroleum energy use than the corn stover ethanol cases.

A comparison of E set gasoline energy use with baseline in 2040 is shown in Figures 9-47 and 9-48. In 2040, two sets of baselines are used: one with corn starch ethanol and the other with corn stover ethanol. With ethanol from corn starch, E set domestic gasolines show about 0-10% reduction in fossil energy and 0-16% reduction in petroleum energy use. With ethanol from corn stover, E set domestic gasolines show about 0-15 % reduction in both fossil energy and petroleum energy use, but much higher total energy use than baseline (up to 20% higher).

Comparing of the 2022 cases and the 2040 cases shows that the latter has higher total energy use, but lower fossil energy use and lower petroleum use than the former (1%–4% lower). It is worth mentioning that the difference is not solely caused by the HOF market share change from 50% to 100% from 2022 to 2040. Many other factors contribute to the changes in domestic gasoline WTW GHG emissions, such as crude slate changes (for PADD cases, not configuration cases), refinery products changes (e.g., G/D ratio change), and U.S. national electricity mix changes. Any changes in the energy use and GHG emissions of refinery products, such as diesel and residual oil, will in turn impact gasoline GHG emissions since they are used along the gasoline WTW lifecycle (e.g., diesel is used for corn growing and transportation, residual oil is used for crude recovery, crude transportation, and refinery processes, and so on).

E set gasoline GHG emissions (g/MJ) in 2022 are shown in Figure 9-49 and 9-50, for both corn starch ethanol and corn stover ethanol, respectively. The results are also shown in Appendix 4 in Table A4-16. For the E set fuels produced in configuration refineries, the exported gasoline burden (GHG emission) is zero for all cases.

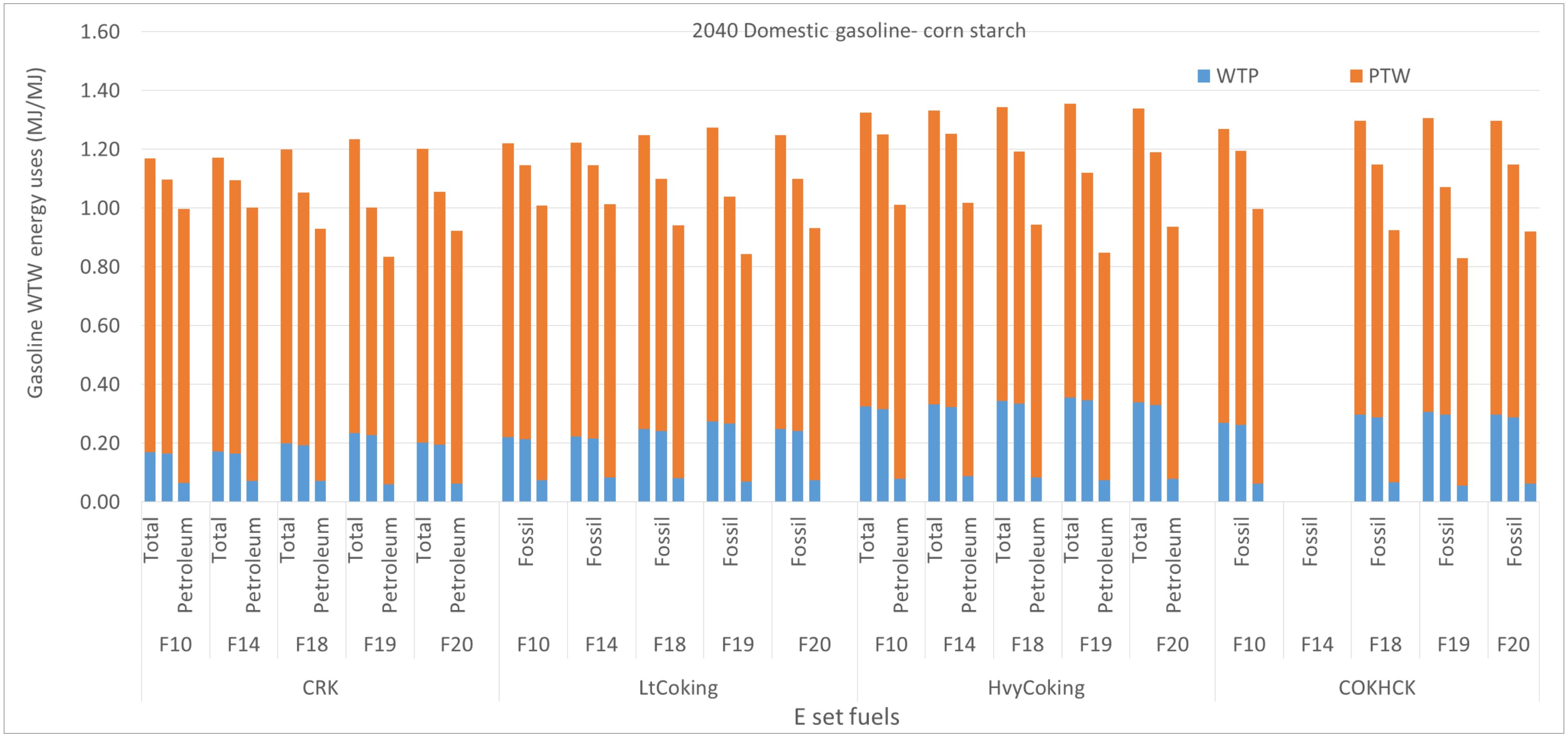


Figure 9-45. WTW Energy Uses of E Set Fuels (Domestic Finished Gasolines) with Corn Starch Ethanol Produced in Configuration Refineries in 2040 Broken Down by WTP and PTW Stage, per MJ basis

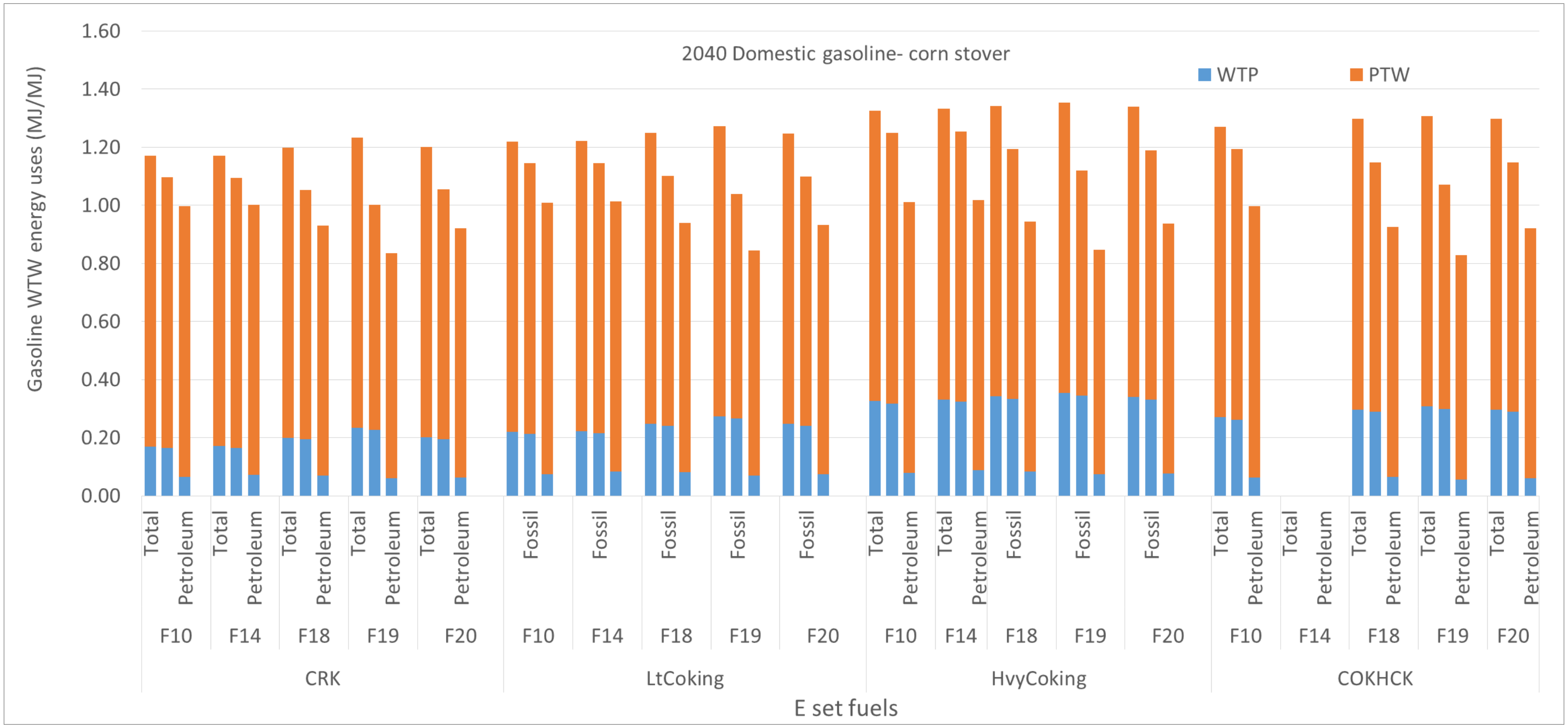


Figure 9-46. WTW Energy Uses of E Set Fuels (Domestic Finished Gasolines) with Corn Stover Ethanol Produced in Configuration Refineries in 2040, Broken Down by WTP and PTW Stage, per MJ basis

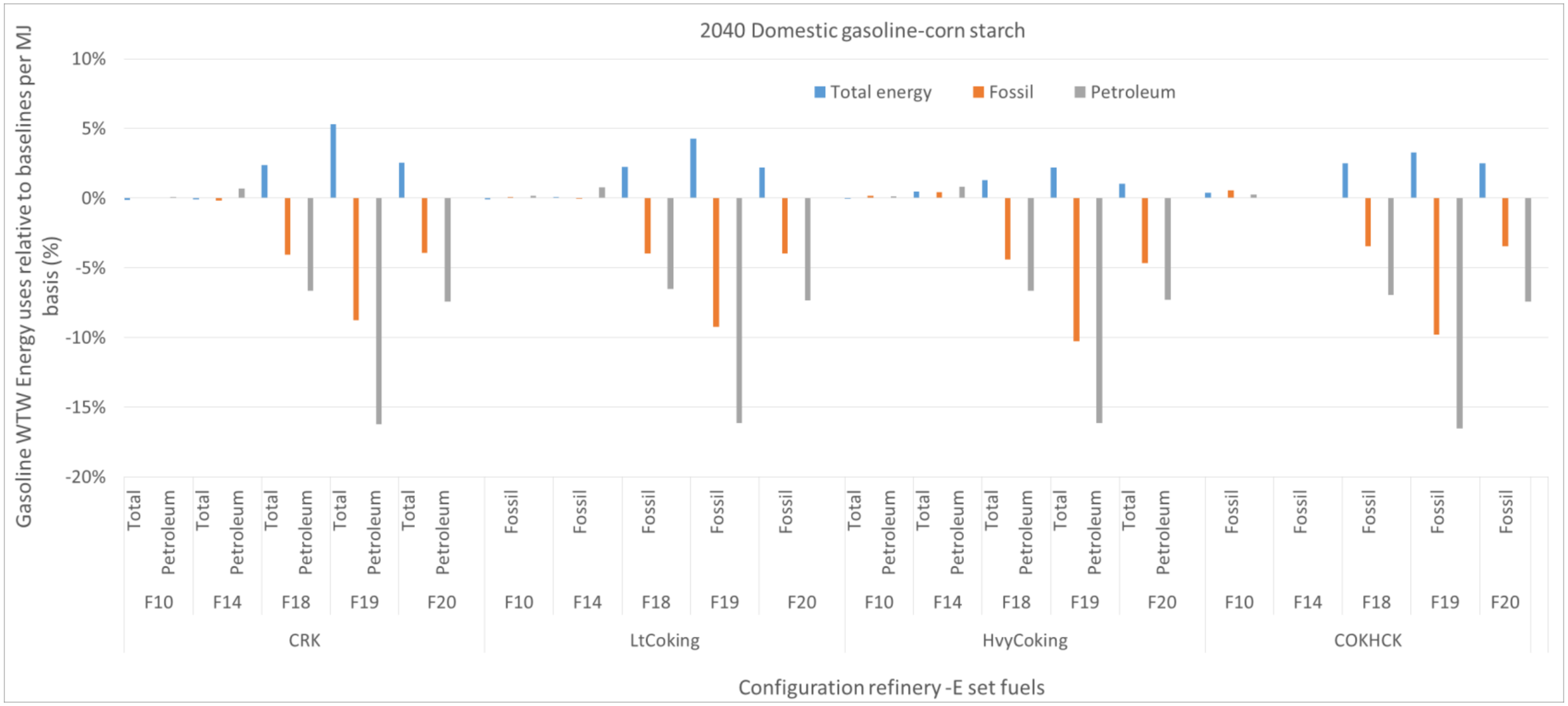


Figure 9-47. Changes of WTW Energy Uses for E Set Domestic Finished Gasolines with Corn Starch Ethanol Relative to Baselines in 2040. Baselines Use Corn Starch Ethanol

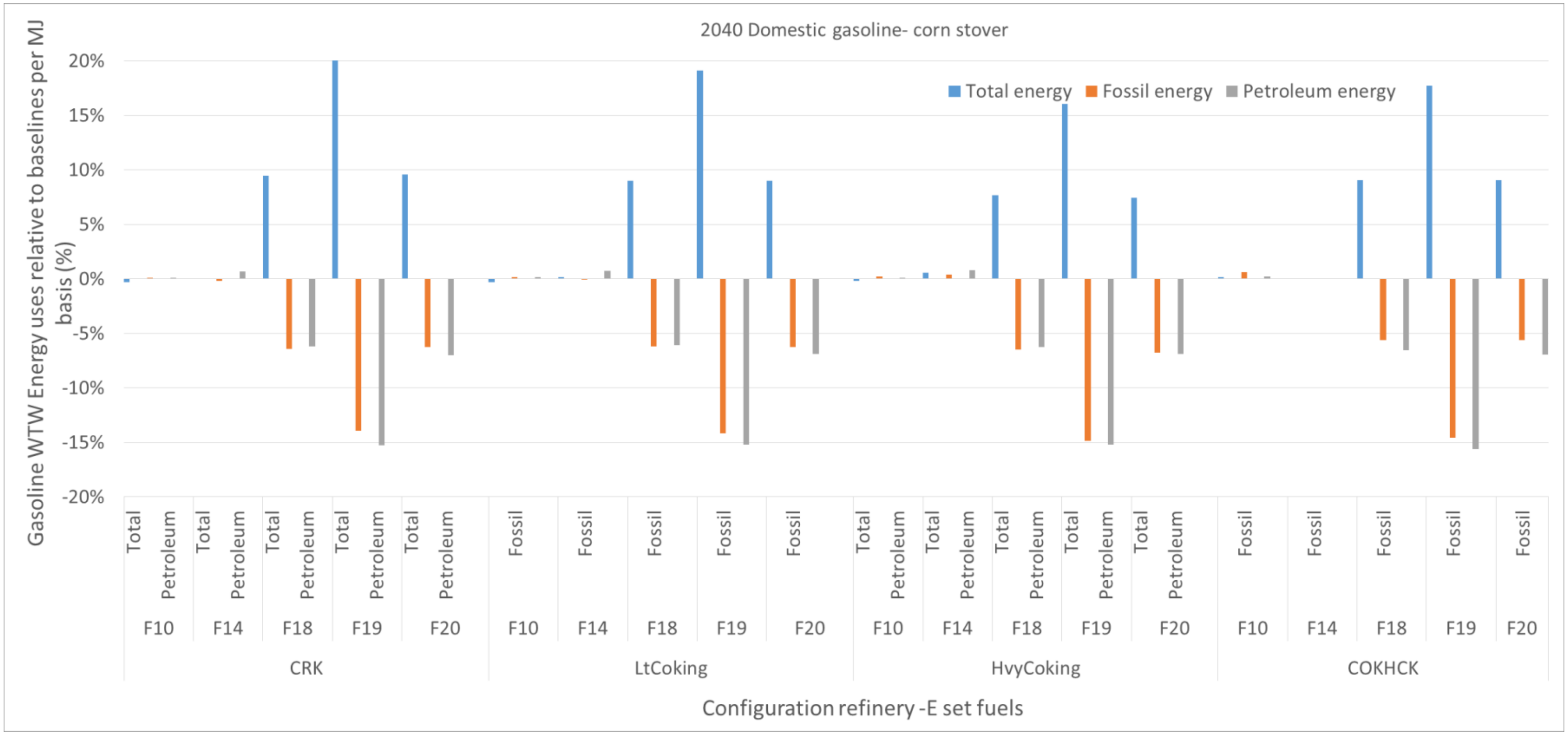


Figure 9-48. Changes of WTW Energy Uses for E Set Domestic Gasoline with Corn Stover Ethanol Relative to Baselines in 2040. Baselines Use Corn Stover Ethanol

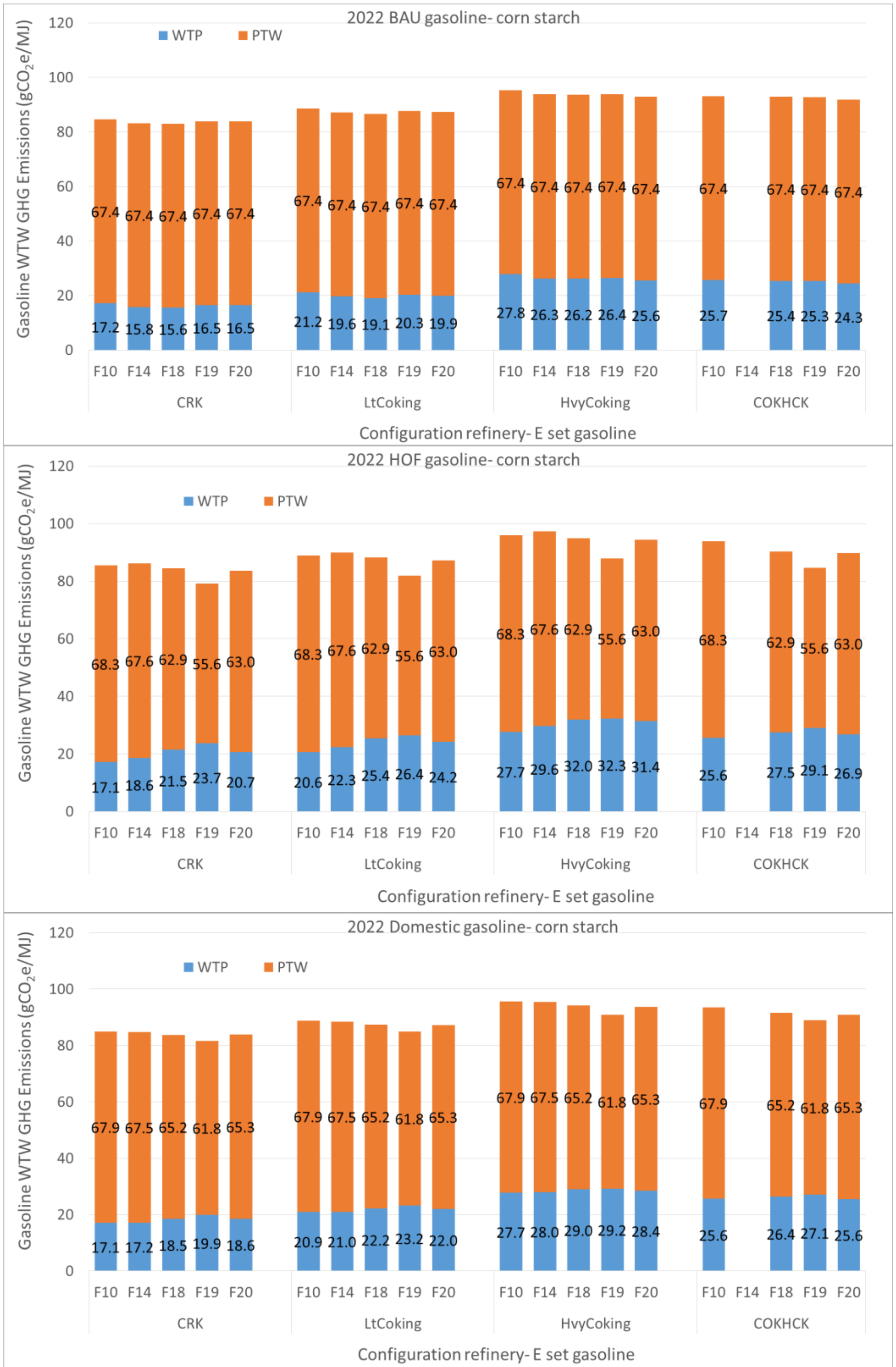


Figure 9-49. WTW GHG Emissions of E Set Finished Gasolines (BAU, HOF and domestic) with Corn Starch Ethanol in Various Configuration Refineries in 2022

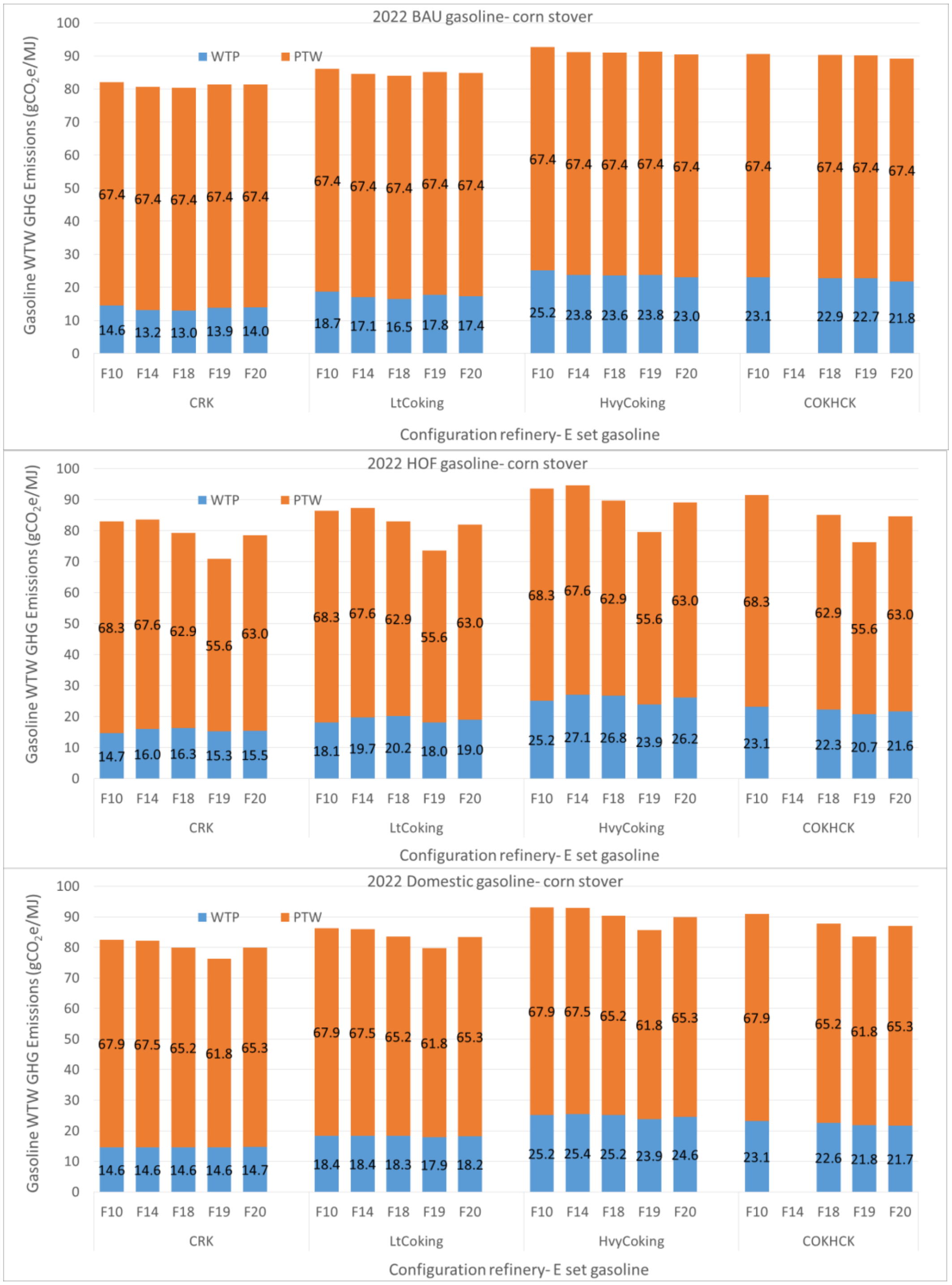


Figure 9-50. WTW GHG Emissions of E Set Gasolines (BAU, HOF and Domestic) with Corn Stover Ethanol in Various Configuration Refineries in 2022

As expected, E set gasolines with corn starch ethanol have higher GHG emissions than gasolines with corn stover ethanol. Consistent with the patterns of energy use just seen, BAU gasoline shows GHG emissions similar to baselines, while HOF gasoline GHG emissions vary with the ethanol blending level.

The relative differences of BAU and HOF gasoline varies from case to case, depending on the fuel, configuration and ethanol source. Fuel 19, with 30% ethanol blending, shows the largest WTW GHG emissions difference between BAU gasoline and HOF gasoline. Combining the WTW GHG emissions of BAU and HOF gasolines results in the GHG emissions of E set domestic gasolines produced in configuration refineries. The results are also shown in Figures 9-49 and Figure 9-50 with ethanol from corn stover and from corn starch, respectively.

In 2040, all domestic gasolines are HOF gasolines, and their GHG emissions are shown in Figure 9-51. The results are also shown in Appendix 4 in Table A4-16.

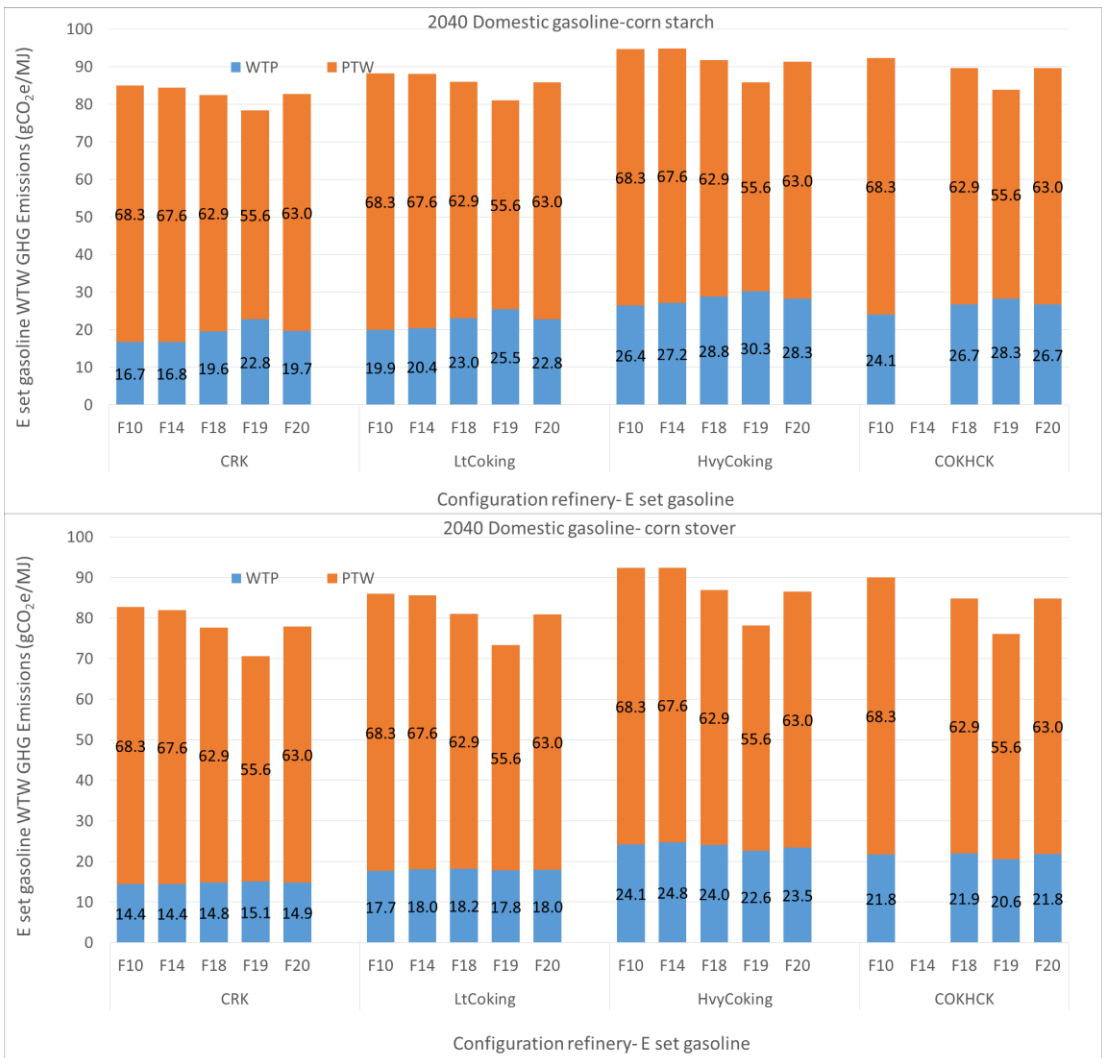


Figure 9-51. WTW GHG Emissions of E Set Gasolines in Various Configuration Refineries in 2040 with Corn Starch Ethanol and Corn Stover Ethanol

E set gasolines with corn stover ethanol show lower GHG emissions than gasolines with corn starch ethanol, and the difference is highly dependent on the ethanol blending level. With 30% ethanol blending, the difference can be 7-8 g/MJ fuel. Domestic gasolines' WTW GHG emissions for both 2022 and 2040 are summarized in Table A4-16 in Appendix 4.

GHG emissions of the E set fuels are compared with those of the configuration refinery base cases in Figure 9-52 below. Again, in 2022, only the base case with corn starch ethanol is used for comparison. For the corn starch cases, Fuel 10 shows slightly higher GHG emissions than baselines (<1%), but lower relative GHG emissions for the 2022 corn stover case. F14 shows marginal changes (both positive and negative changes) compared with baselines. Fuel 19, with 30% ethanol blending, shows the highest GHG reductions, ranging from 4-7% for year 2022 and 6-14% for year 2040. As expected, the E set fuels with ethanol from corn stover show greater reductions of GHG emissions than fuels using ethanol from corn starch.

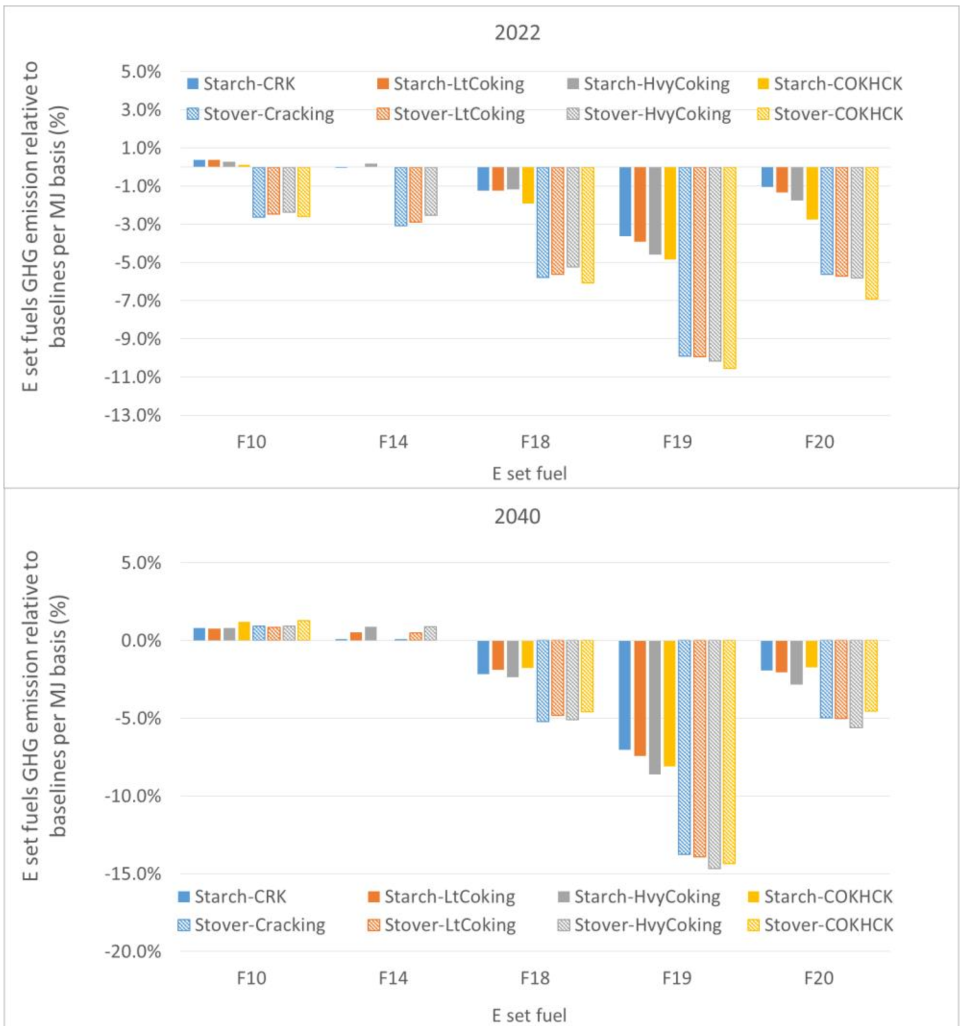


Figure 9-52. Changes of E Set Fuels WTW GHG Emissions (configuration cases) Relative to the Emissions of Baselines per MJ Basis. In 2022 Baselines Use Corn Starch Ethanol. In 2040, Dual Sets of Baselines Are Used with Corn Starch Ethanol and Corn Stove Ethanol

9.1.4.2 Configuration E Set Fuels WTW Energy Use and GHG Emissions Per Mile Driven

WTW energy uses of E set BAU and HOF gasolines for 2022 were converted to the results for a per-mile basis. The energy use for BAU, HOF and domestic gasolines, broken down by WTP and PTW, is shown in Figure 9-53 for the 2022 corn starch ethanol case.

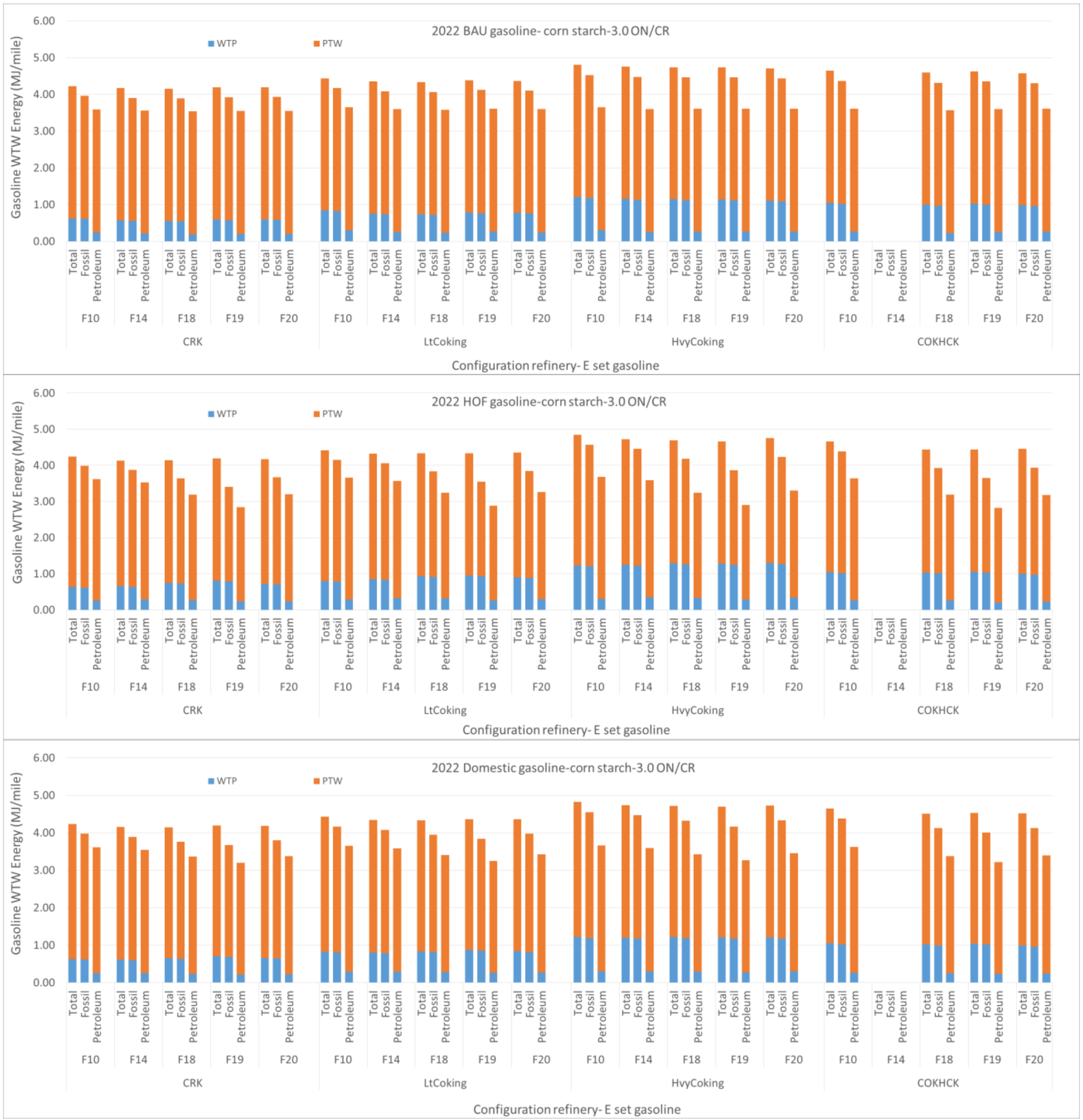


Figure 9-53. WTW Energy Use of E Set Gasolines with Corn Starch Ethanol in Configuration Refineries in 2022, Per-Mile Basis (for ON/CR 3.0)

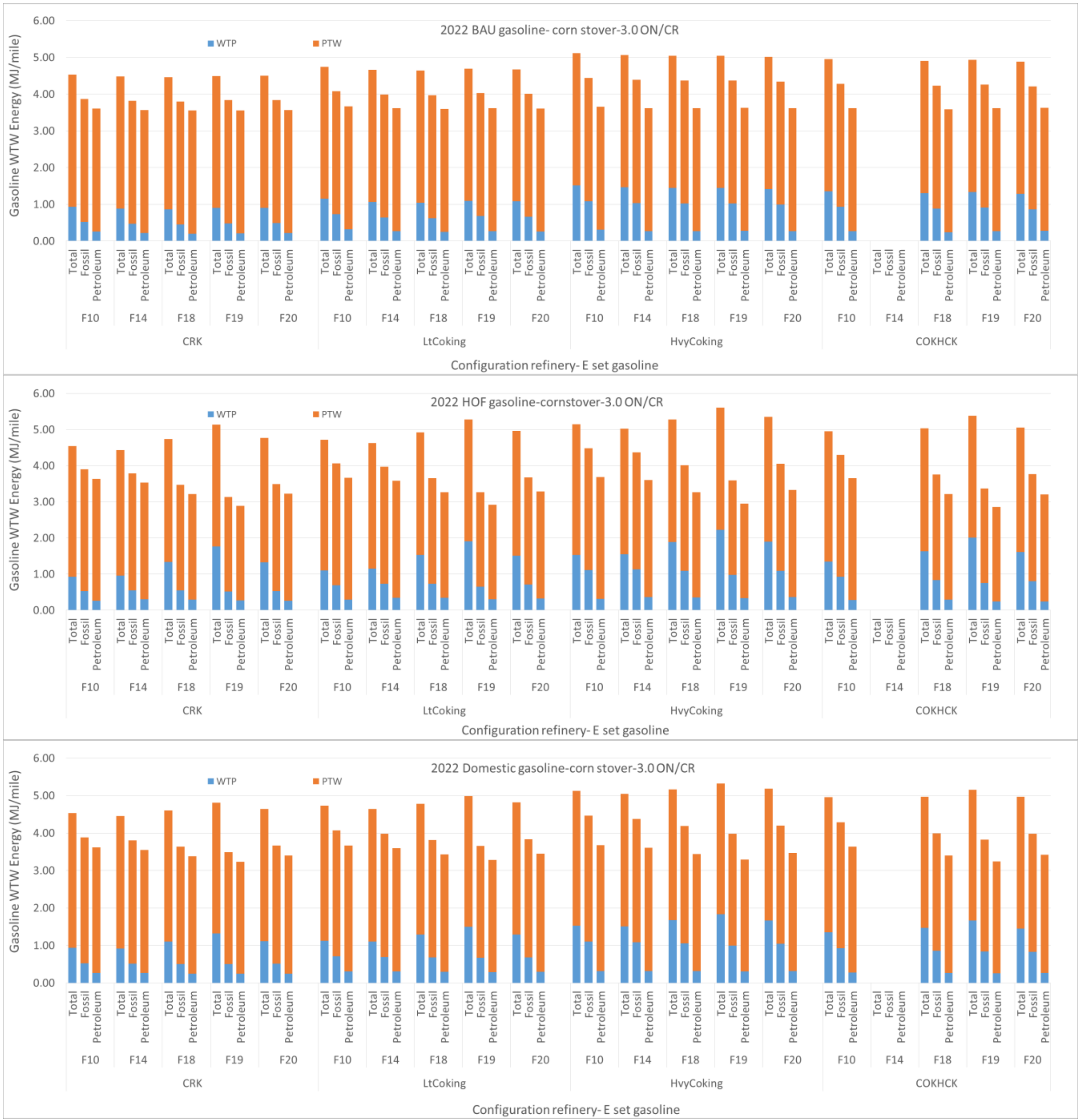


Figure 9-54. WTW Energy Use of E Set Gasolines with Corn Stover Ethanol in Configuration Refineries in 2022, Per-Mile Basis (for ON/CR of 3.0)

E set gasoline energy use per mile shows trends similar to that for the per-MJ basis. Fuel 19 shows greater energy use reductions per mile driven than per MJ fuel, owing to fuel economy gains enabled by its high RON. F14, the mid RON E10 fuel, has the lowest total energy use per mile in all cases for 2022.

The WTW energy use of BAU gasolines are also listed in Table A4-17 in Appendix 4. WTW energy use for HOF gasoline with corn starch ethanol and corn stover ethanol are shown in appendix 4 in Table A4-18, with three sets of assumed ON/CR values for year 2022. The WTW energy uses of E set domestic gasolines for 2020 are shown in appendix 4 in Table A4-19.

The WTW energy uses of E set domestic gasolines for 2040 are shown in Figure 9-55. The results are also shown in appendix 4 in Table A4-20 for details.

The different CR/ON assumptions for high-octane fuels have little impact on overall WTW energy use (1.7% for the most pronounced case). The relative energy use changes per mile of E set domestic gasoline compared with baselines is shown in Figures 9-56 and 9-57, for 2022 and 2040, respectively.

Although the WTW energy use per mile of E set gasolines increases with increasing refinery complexity, its changes compared with baseline (specific for each refinery configuration) remain similar. For example, in 2022, compared with baselines with corn starch ethanol, Fuel 19 with corn starch ethanol can reduce fossil energy use per mile by 7-8% and petroleum energy by over 11%, although total energy use per mile reduction is about 1%–2% higher. Compared to baselines with corn starch ethanol, Fuel 19 with corn stover ethanol can reduce fossil energy use by 12-13% and petroleum energy use per mile by about 10%, but total energy increases by 10-15%.

As shown in Figure 9-57, compared with baselines with corn starch ethanol, in 2040 Fuel 19 with corn starch ethanol can reduce fossil energy use per mile by 14-15% and petroleum energy use by over 22%, although total energy use per mile savings is less than 2%. Compared to baselines with corn starch ethanol, F19 with corn stover ethanol can reduce both fossil energy use per mile and petroleum energy use mile by 20%, although total energy use per mile increases by 9-14%. The different ON/CR assumptions lead to only minor changes to the comparison and are not shown here for brevity.

E set gasoline WTW GHG emissions on a per-mile basis were also investigated. GHG emissions of BAU, HOF and domestic gasolines in 2022 are shown in Figure 9-58, broken down by WTP and PTW stages for ON/CR of 3.0.

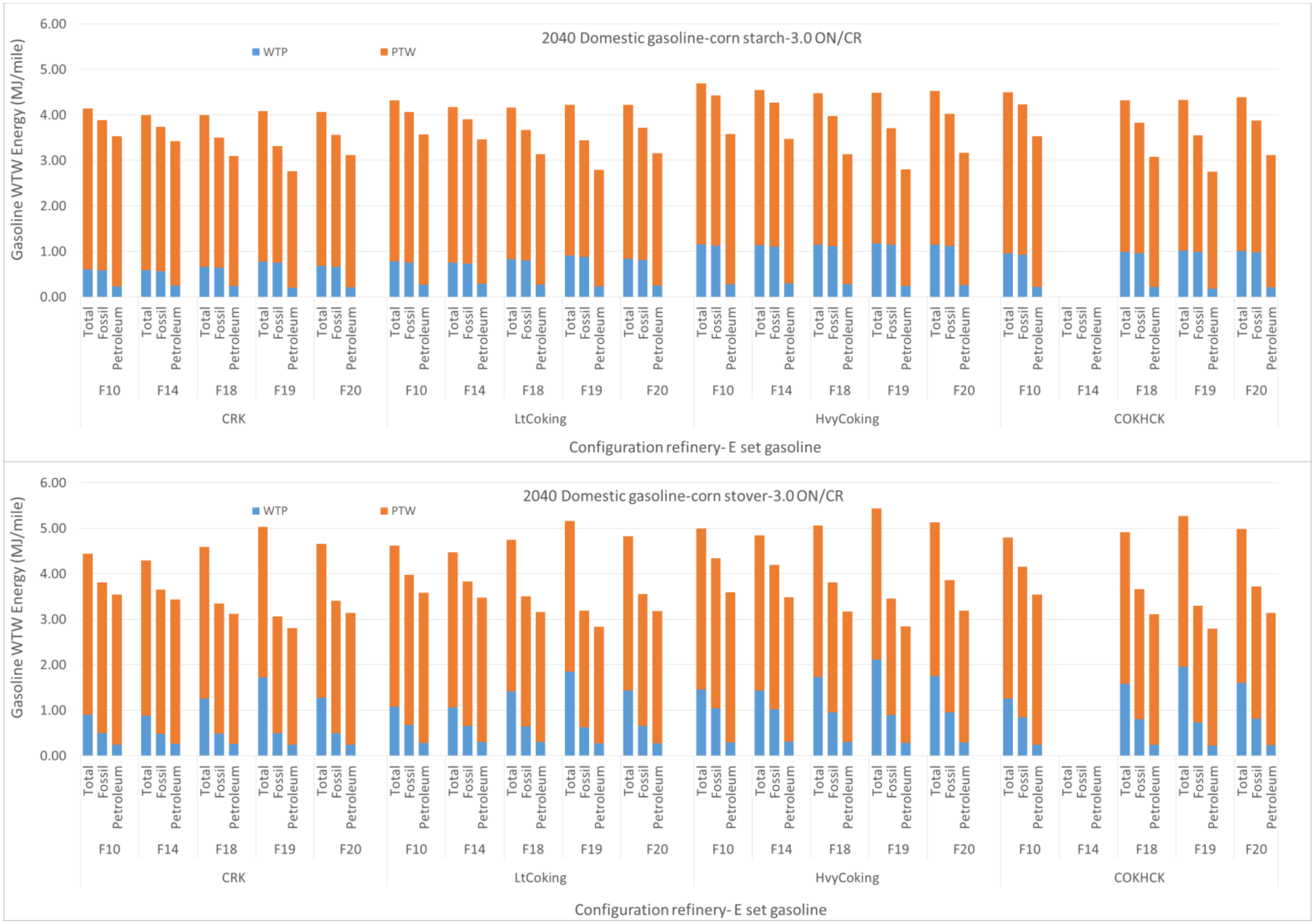
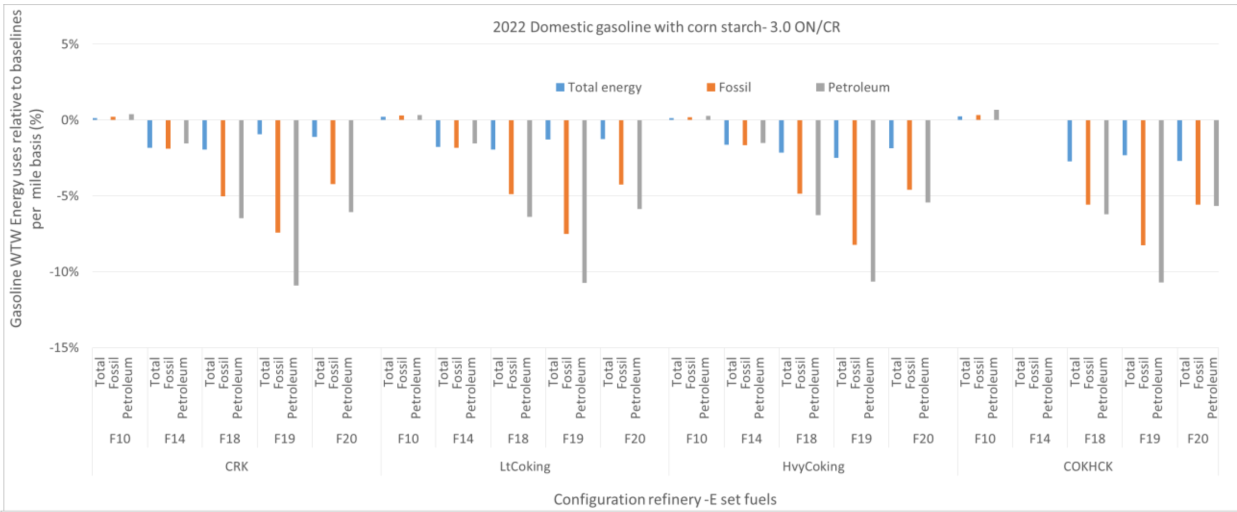


Figure 9-55. WTW Energy Use of E Set Domestic Finished Gasolines with Corn Starch Ethanol and Corn Stover Ethanol in Configuration Refineries in 2040, Per-Mile Basis (for ON/CR of 3.0)



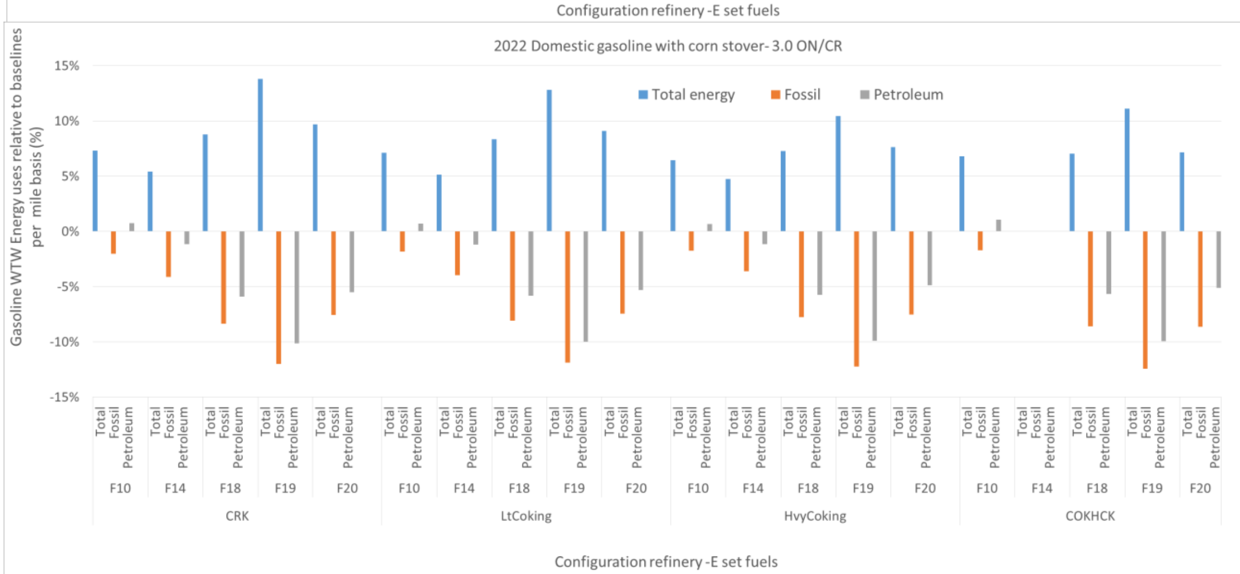


Figure 9-56. Comparison of E Set Domestic Gasolines WTW Energy Uses with Baselines in 2022 in Configuration Refineries with Corn Starch and Corn Stover Ethanol (for ON/CR of 3.0). Baselines Use Corn Starch Ethanol

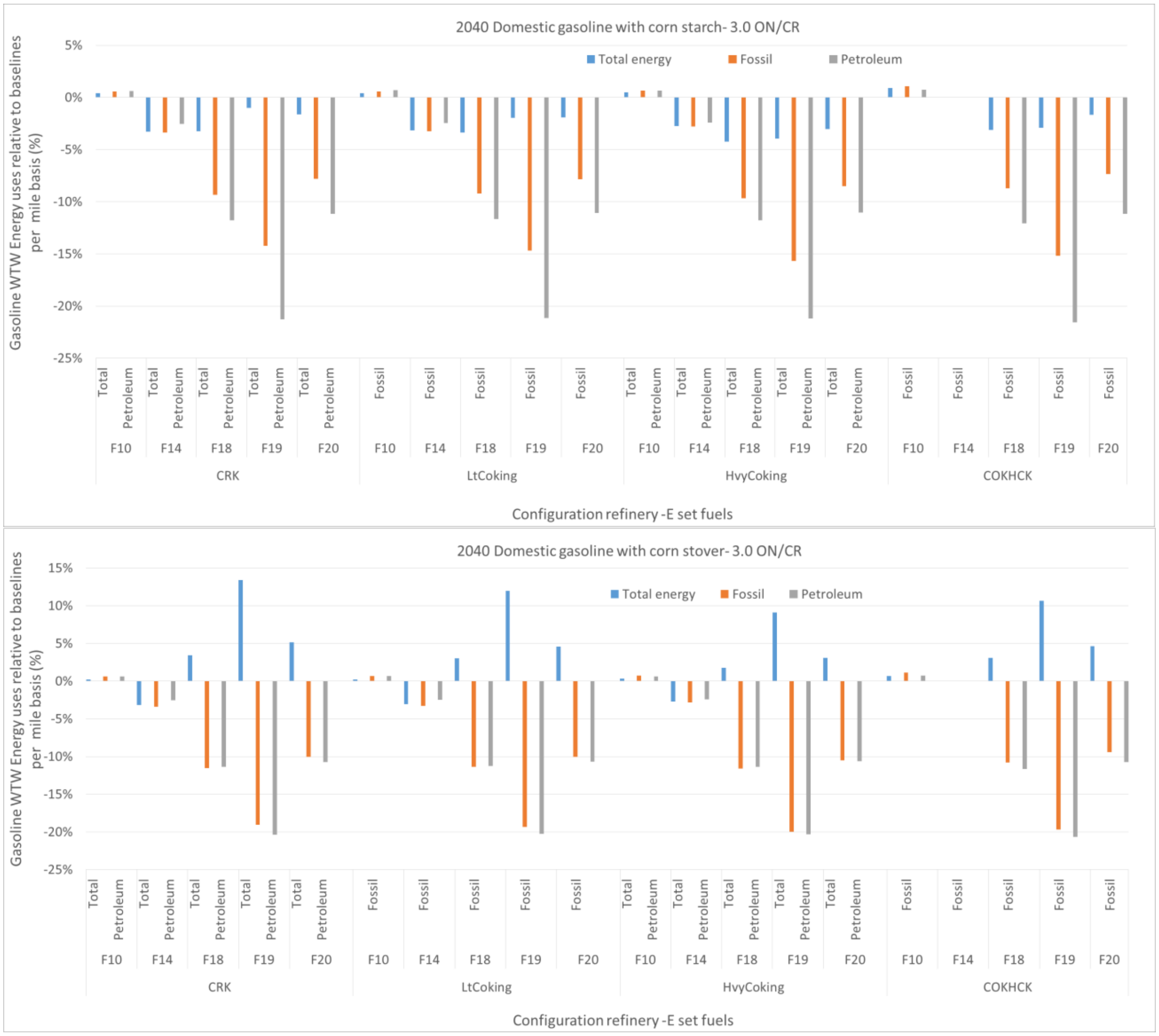


Figure 9-57. Comparison of E Set Domestic Finished Gasolines (with Corn Starch and Corn Stover Ethanol) WTW Energy Use with Baseline, in 2040 in Configuration Refineries (for ON/CR of 3.0). Dual Sets of Baselines Used

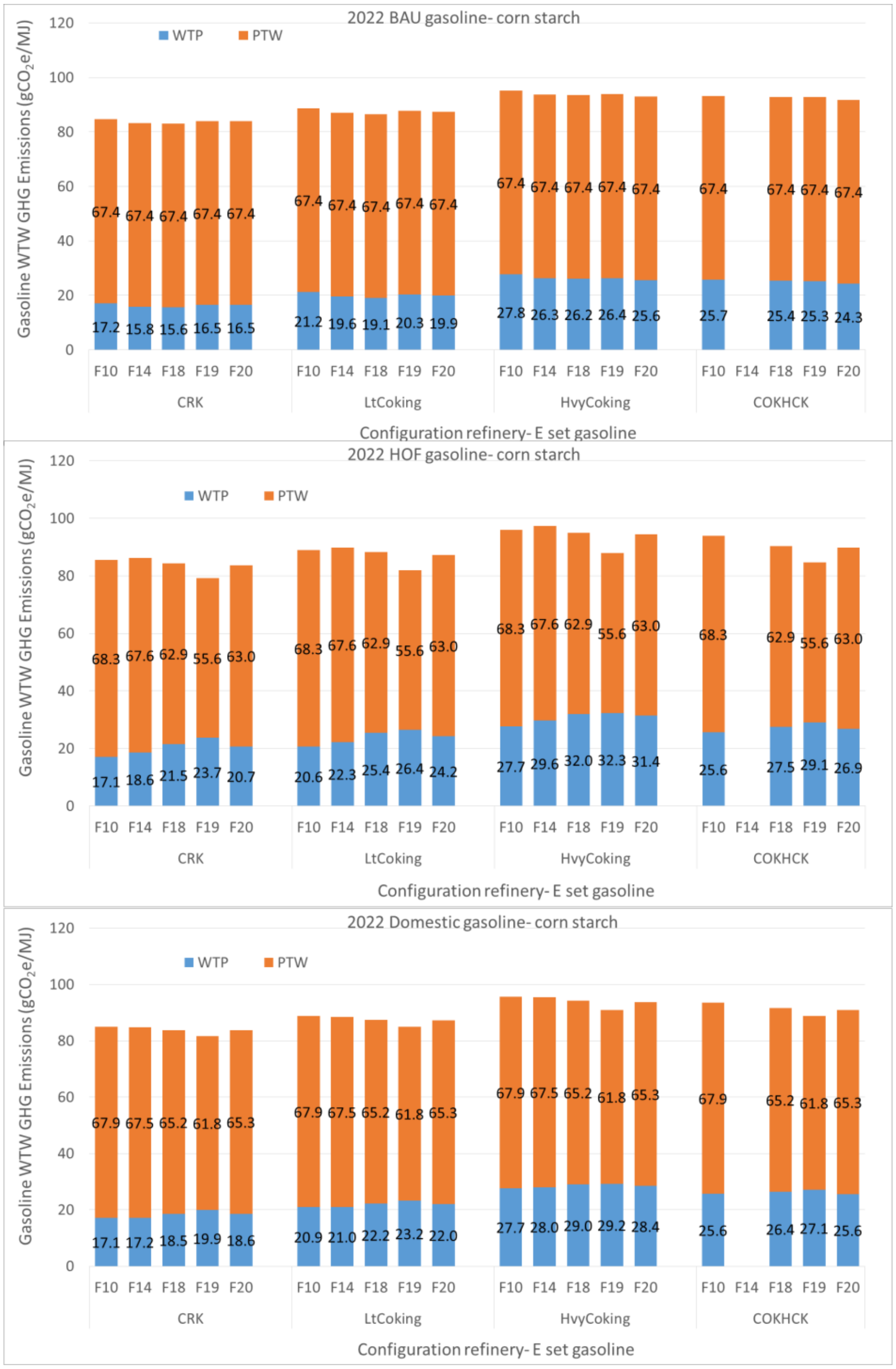


Figure 9-58. 2022 WTW GHG Emissions of E Set BAU, HOF and Domestic Gasolines in Configuration Refineries with Ethanol from Corn Starch (for ON/CR of 3.0)

Again, all BAU gasoline has GHG emissions similar to baselines, and HOF gasoline GHG emissions vary with the ethanol blending level. GHG emissions with other ON/CR assumptions and with corn stover ethanol show similar trends, are summarized in Appendix 4 in Table A4-21.The various ON/CR assumptions have little impact on HOF WTW GHG emission—about 1%–5 g/mile.

E set domestic gasoline pool GHG emissions on a per-mile basis, with three scenarios of 3 ON/CR, 3.7 ON/CR and 5.6 ON/CR, are shown in Table 9-11.

As expected, E set fuels GHG emissions increase with increasing configuration refinery complexity, in the order of CRK < LtCOK < COKHCK < HvyCOK. For each E set fuel, the GHG emissions of the domestic gasoline pools (i.e., combined results of BAU gasoline GHG emissions and HOF gasoline GHG emissions) change slightly (1–2 g/mile) with different fuel economy assumptions, as shown in Table 9-12. Overall, the value of ON/CR has less than 1% impact across the values studied.

Table 9-11. E Set Domestic Finished Gasoline GHG Emissions (g/mile) with Various ON/CR Values in 2022

		Corn Starch (g/mile)				Corn Stover (g/mile)			
2022 Configuration	Fuel	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR
CRK	F10	306.5	--	--	--	297.4	--	--	--
	F14	--	299.6	300.5	301.8		290.5	291.4	292.6
	F18	--	292.5	293.6	295.4		279.0	280.0	281.7
	F19	--	284.9	285.9	287.6		266.4	267.3	268.9
	F20	--	295.3	296.2	297.6		281.6	282.6	283.9
LtCOK	F10	320.1	--	--	--	311.0	--	--	--
	F14	--	312.9	313.9	315.2		303.8	304.8	306.1
	F18	--	305.4	306.5	308.4		291.9	293.0	294.7
	F19	--	296.6	297.6	299.4		278.0	279.0	280.7
	F20	--	307.4	308.4	309.9		293.8	294.8	296.1
HvyCOK	F10	344.6	--	--	--	335.5	--	--	--
	F14	--	337.8	338.9	340.3		328.7	329.7	331.1
	F18	--	329.4	330.5	332.5		315.9	317.0	318.9
	F19	--	317.4	318.5	320.4		298.8	299.9	301.7
	F20	--	329.9	331.0	332.5		316.3	317.4	318.8
COKHCK	F10	337.1	--	--	--	328.0	--	--	--
	F18	--	320.3	321.4	323.4		306.8	307.8	309.7
	F19	--	310.1	311.2	313.1		291.6	292.6	294.3
	F20	--	319.9	321.0	322.5		306.3	307.3	308.7

Table 9-12. E Set Fuels (Domestic Finished Gasoliness) GHG Emissions (g/mile) with Various ON/CR Values in 2040

		Corn Starch				Corn Stover			
2040 Configuration	Fuel	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR	CR 10.5	3 ON/CR	3.7 ON/CR	5.6 ON/CR
CRK	F10	301.0				293.0			
	F14		287.9	289.7	292.0		279.7	281.5	283.8
	F18		274.8	276.7	280.1		258.8	260.6	263.7
	F19		259.6	261.5	264.7		234.1	235.8	238.7
	F20		279.6	281.4	284.0		263.3	265.1	267.5
LtCOK	F10	312.5				304.4			
	F14		300.3	302.1	304.6		292.1	294.0	296.4
	F18		286.2	288.2	291.7		270.2	272.1	275.4
	F19		268.6	270.5	273.8		243.1	244.8	247.8
	F20		290.0	291.9	294.6		273.8	275.6	278.1
HvyCOK	F10	335.4				327.4			
	F14		323.3	325.3	328.0		315.2	317.2	319.8
	F18		305.6	307.7	311.4		289.6	291.6	295.1
	F19		284.4	286.5	290.0		258.9	260.8	264.0
	F20		308.6	310.7	313.5		292.4	294.3	297.0
COKHCK	F10	327.0				319.0			
	F18		298.5	300.6	304.3		282.6	284.5	288.0
	F19		277.8	279.7	283.2		252.3	254.0	257.2
	F20		303.2	305.2	308.0		286.9	288.8	291.5

Compared to the E set fuels GHG emissions in 2022, the E set fuels in 2040 have lower emissions because of improved vehicle fuel economies. Varying the ON/CR assumptions has a greater impact on GHG emissions in 2040 because all the E set gasoline fuels are HOF (which is subject to the fuel economy change), while in 2022, only half the domestic gasoline fuels are HOF.

A comparison of E set fuels GHG emissions with base case E10 GHG emissions is shown in Figure 9-59.

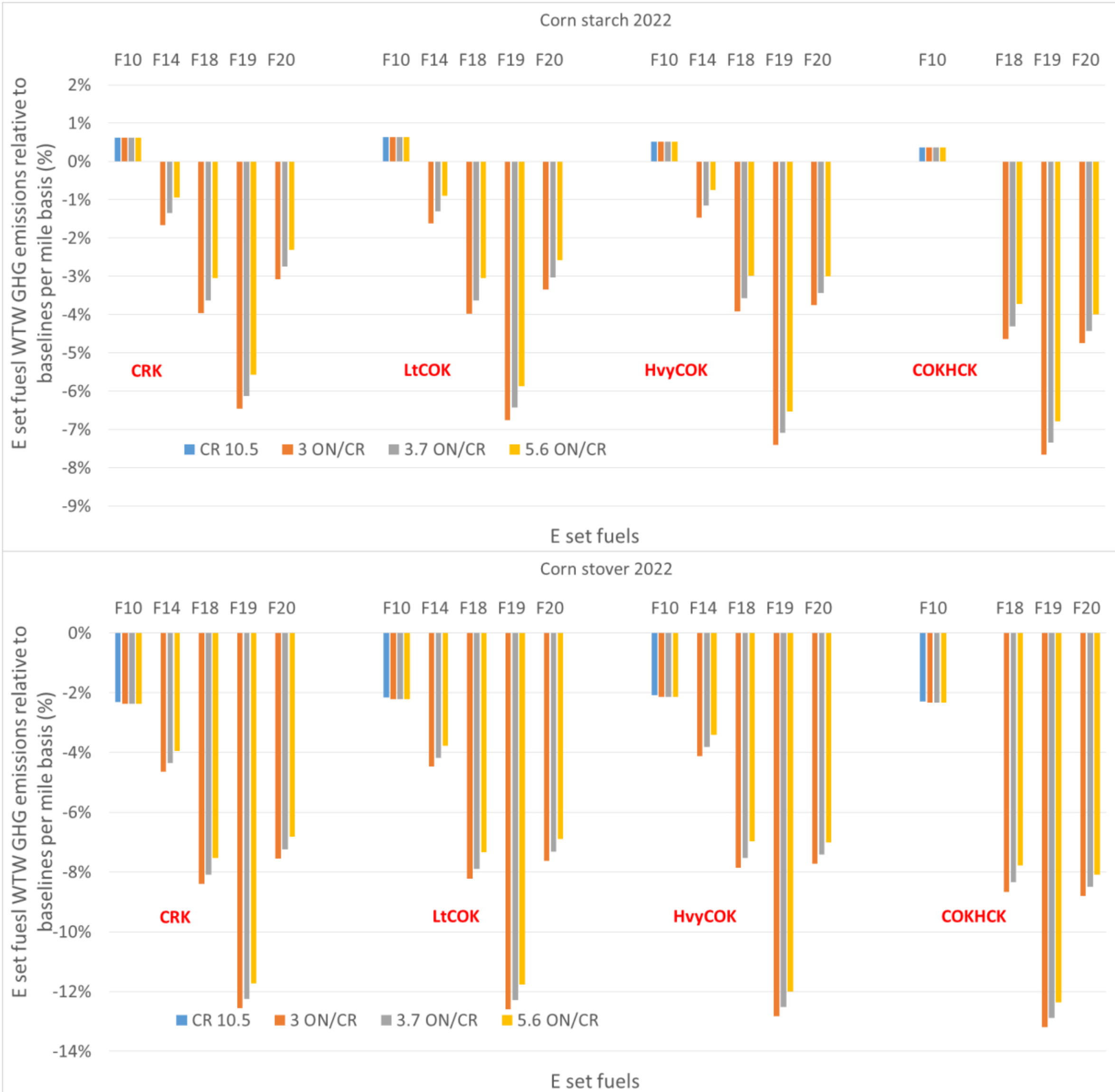


Figure 9-59. Comparison of WTW GHG Emissions of E Set Domestic Gasolines (produced in configuration refineries) with Baselines in 2022 (for ON/CR=3.0). Baselines Use Corn Starch Ethanol

For all configuration cases, Fuel 10 has higher WTW GHG emissions than baselines for corn starch, but not corn stover. The GHG reduction is strongly dependent on ethanol blending levels. As expected, Fuel 19 has the largest GHG emission reductions compared with baselines, reaching about 9-11% for corn stover cases and 6-8% for corn starch cases.

Compared with 2022, 2040 cases show greater GHG reductions. For example, Fuel 19 has the greatest GHG reductions compared with baselines, reaching 17-19% for corn stover cases and 11%–14% for corn starch cases, as shown in Figure 9-60.

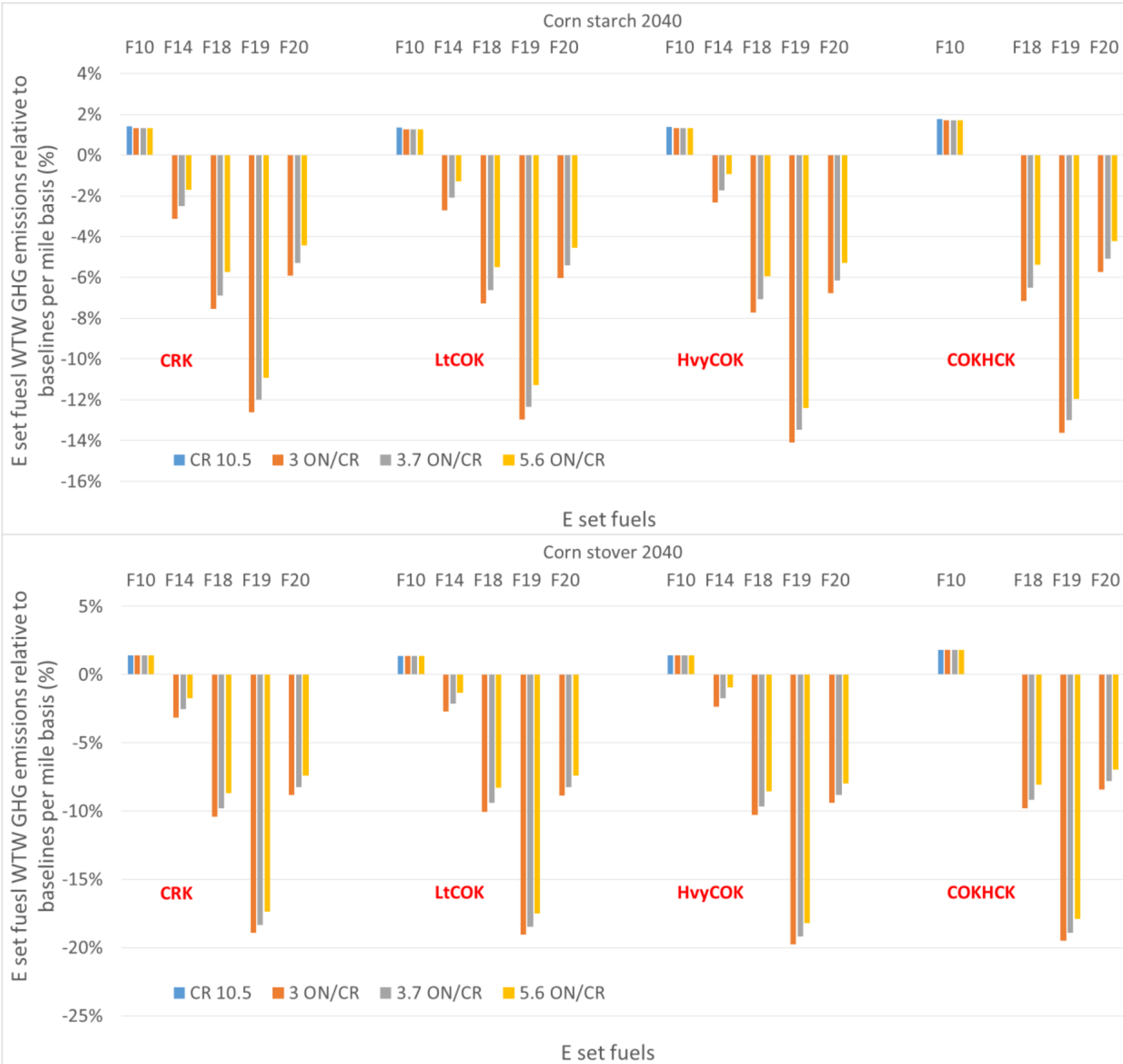


Figure 9-60. Comparison of WTW GHG Emissions of E Set Domestic Gasolines (Produced in configuration refineries) with Baselines in 2040 (for ON/CR=3.0). Dual Sets of Baselines Used with Corn Starch Ethanol and Corn Stover Ethanol, Respectively

For both 2022 and 2040, F10 shows slightly higher GHG emissions than baselines. This is because with an octane of 91, F10 has same fuel economy as baseline and does not gain the additional fuel economy enabled by high octane. The refinery configuration has a moderate impact on the GHG emissions per mile, 10-30 g/mile, but barely impacts change compared with baselines.

9.2 WTW Energy and GHG Results of BR Set Fuels

9.2.1 WTW Analysis of BR Set Fuels from Aggregate Refineries

WTW energy use and GHG emissions for BR set fuels from aggregate refineries were determined by combining the WTP results with the PTW results. LP modeling of the BOBs to blend with ethanol and

BR (for the production of BAU and HOF in 2022 and for HOF in 2040) was carried out for PADD 2 and PADD 3 only, as LP modeling of BR cases in CA did not yield feasible solutions, likely caused by the aromatic limitation in CA. The analysis of BR stream production was carried out for three processes differentiated by the hydrogen supply source: purchased hydrogen, in-situ hydrogen production and gasification hydrogen (described in Section 5).

The impact of PADD refinery, hydrogen source, and BR stream pathway is illustrated by comparing the WTW results of BR set fuels with different cases.

9.2.1.1 Per-MJ BR Fuel WTW Energy Use and GHG Emissions in Two PADDs

WTW energy use of the BR set BAU gasolines in 2022 are shown in Figure 9-61, broken down into WTP and PTW stages.

The BR BAU gasolines produced in PADD 2 have higher energy use than those produced in PADD 3, which is again attributable to the use of oil sands in the feedstock stage in PADD 2. The BR BAU gasolines have 10% ethanol blending (without bioreformate), so differences in energy use among BAU gasolines with different ethanol sources are relatively small. The BAU gasolines with corn starch ethanol have lower total energy use and higher fossil energy use than the BAU gasolines with corn stover ethanol, but with similar petroleum energy use.

WTW energy use for BR HOF gasolines in 2022 is shown in Figure 9-62 for the three different sources of hydrogen.

For a given hydrogen source, BR HOF gasoline has higher energy use in PADD 2 than in PADD 3. As was the case with ethanol blending, total energy use increases with increasing levels of BR blending (BR1-T has 9 vol% BR blending while BR2 and BR 4-T have 27 vol% blending). For a given BR HOF gasoline, energy use with purchased H_2 has the highest fossil energy use in the feedstock stage, as hydrogen production in this pathway consumes natural gas. The BR HOF with in-situ H_2 has the highest total energy use in the feedstock stage, as hydrogen production in this pathway consumes bio-intermediate (hydrolysates produced from enzymatic hydrolysis, see Figure 4-3). The BR HOF with gasification H_2 has moderate total energy use compared to the other two options, but shows the lowest fossil energy use. Note that the bioreformate production with different hydrogen sources not only refers to the different energy uses for the hydrogen, but also accounts for overall energy and material input or consumption differences derived from various hydrogen supply options through the bioreformate WTP production (e.g., electricity, sulfuric acid, glucose, etc., see Table 4-8).

With BAU gasoline having two sets of results (two ethanol sources) and HOF gasoline having three sets of results (three hydrogen sources), the combined domestic gasolines have six sets of results in 2022. In 2040, there are only three sets of energy use results for domestic gasolines, as all domestic gasolines are HOF with bioreformate blending but without ethanol. The WTW energy use of the combined domestic gasoline pools for the BR set fuels for 2022 and 2040 are shown in Figures 9-63, 9-64 and 9-65.

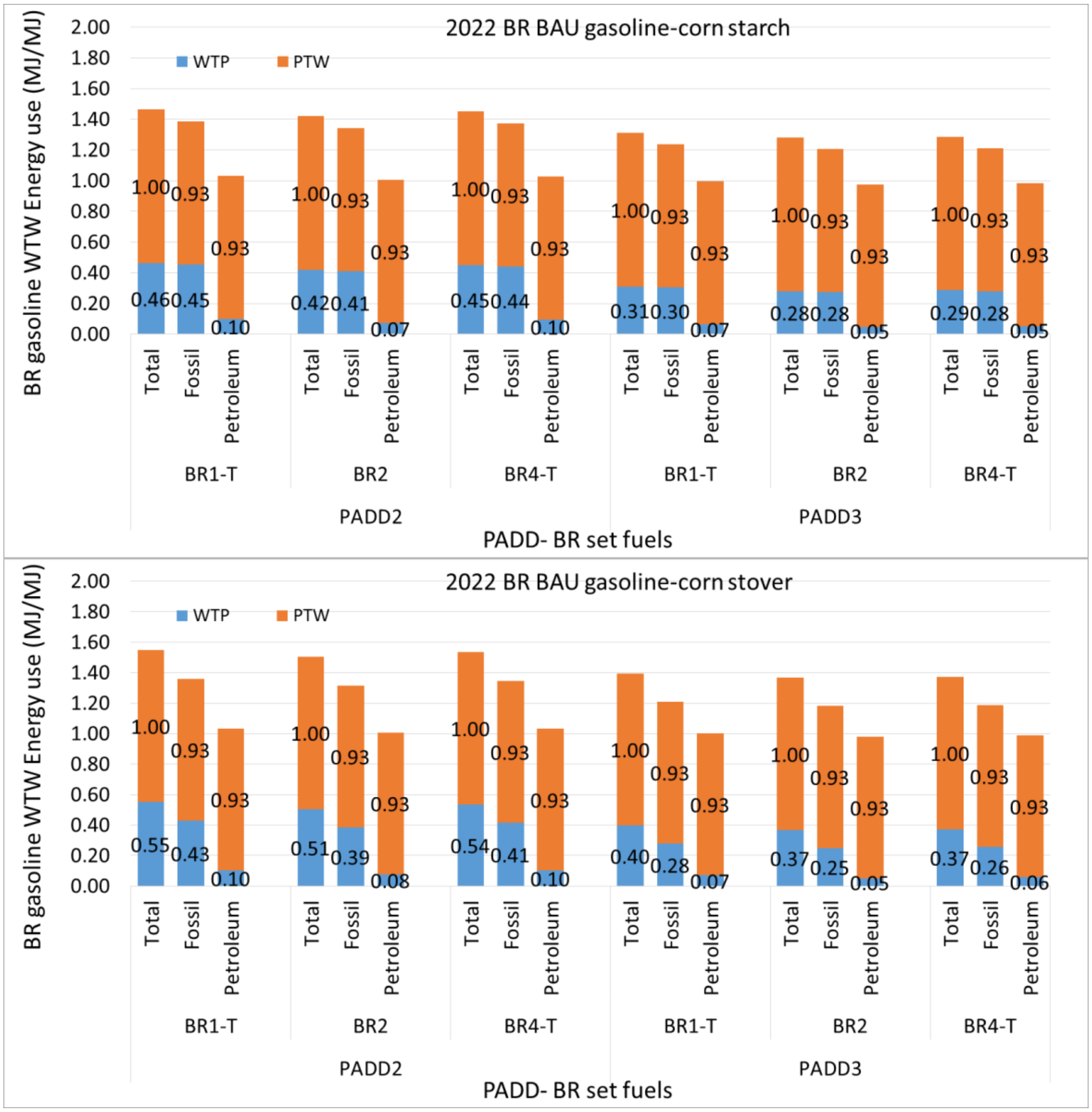


Figure 9-61. WTW Energy Use of the BR Set BAU Gasolines with Corn Starch Ethanol and Corn Stover Ethanol

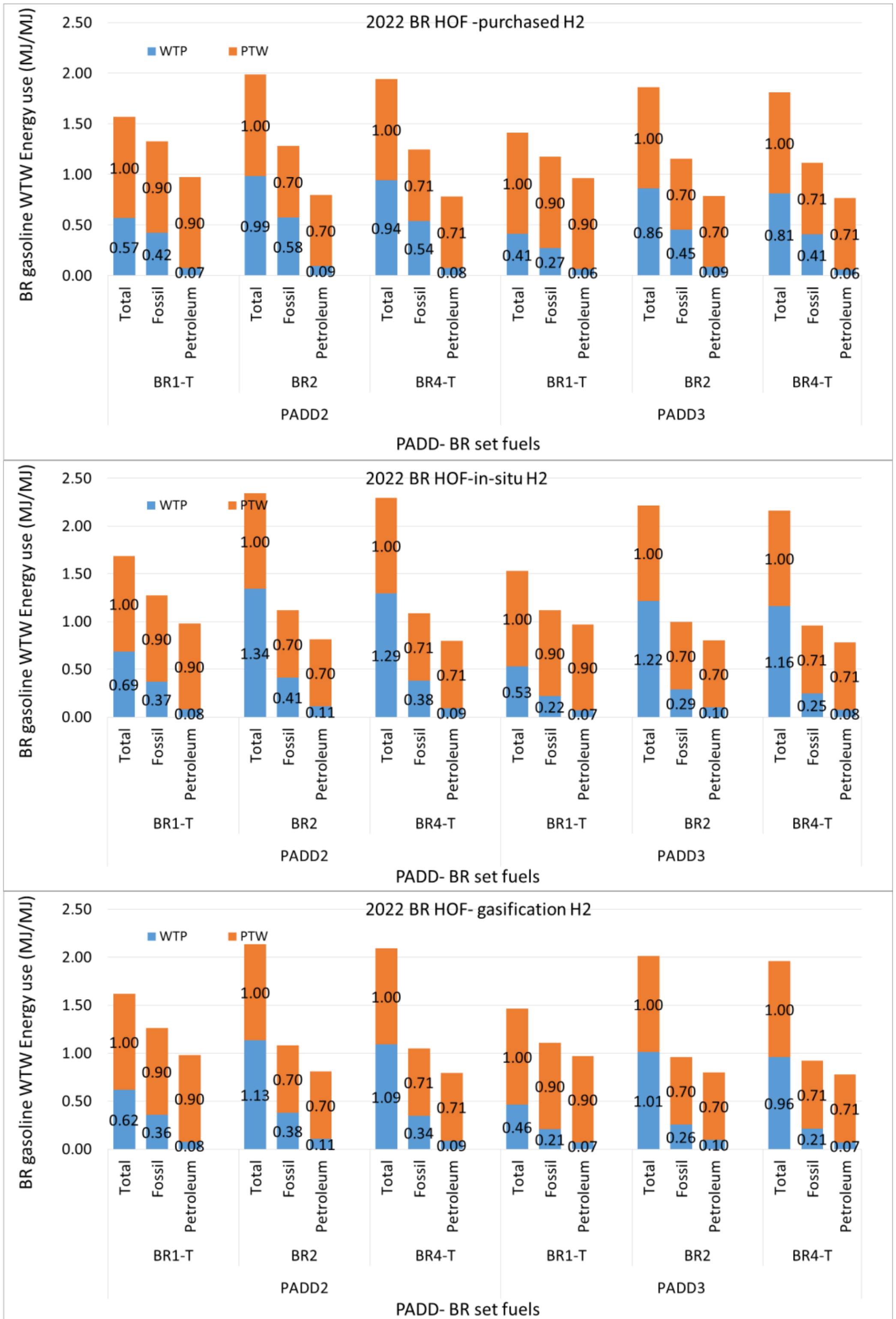


Figure 9-62. WTW Energy Use of the BR Set HOF Gasolines in 2022, with Bioreformate Produced with Three Different Sources of Hydrogen

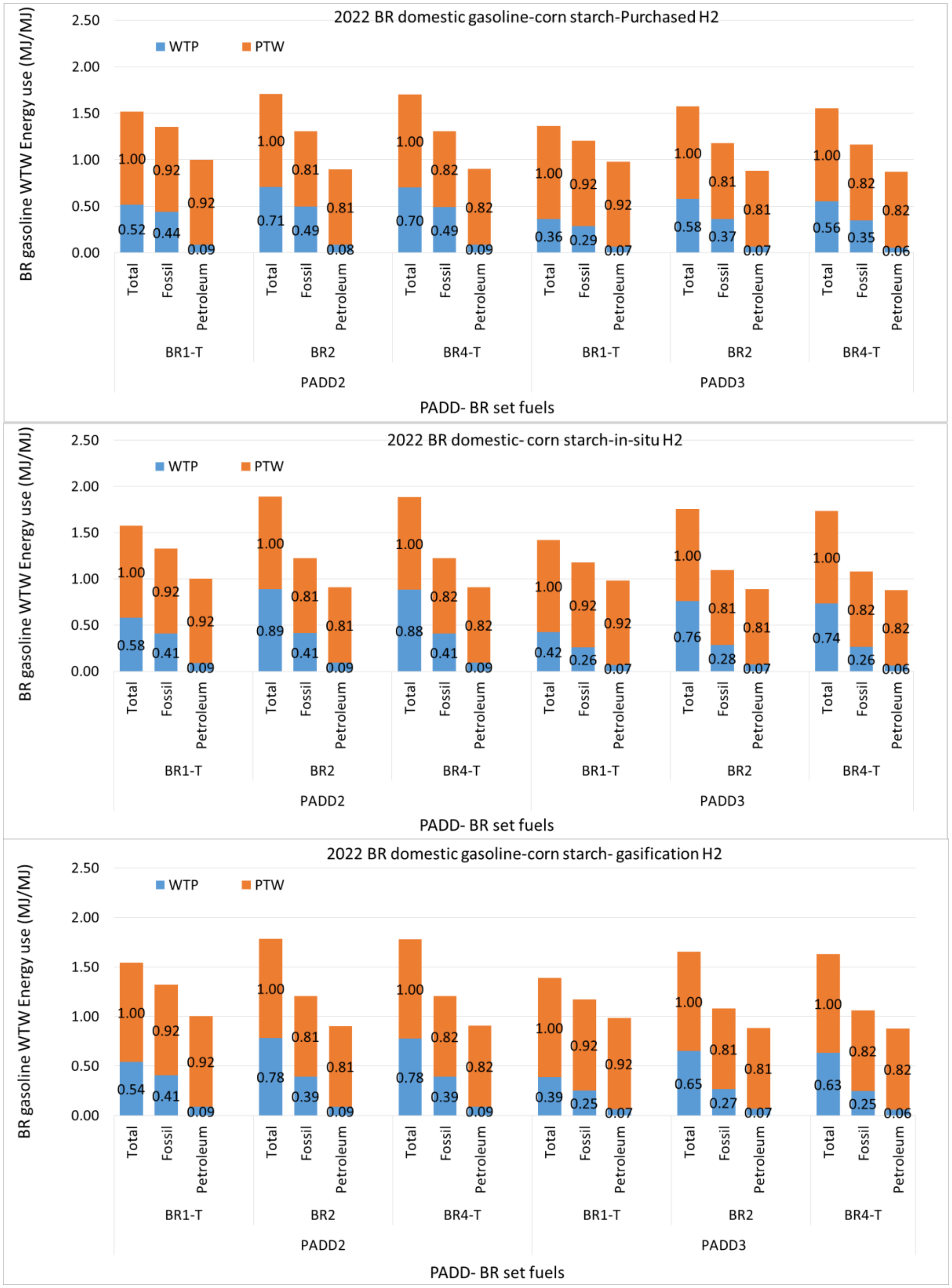


Figure 9-63. 2022 BR Set Domestic Finished Gasolines WTW Energy Uses with Ethanol from Corn Starch and Bioreformate Produced from Three Hydrogen Sources

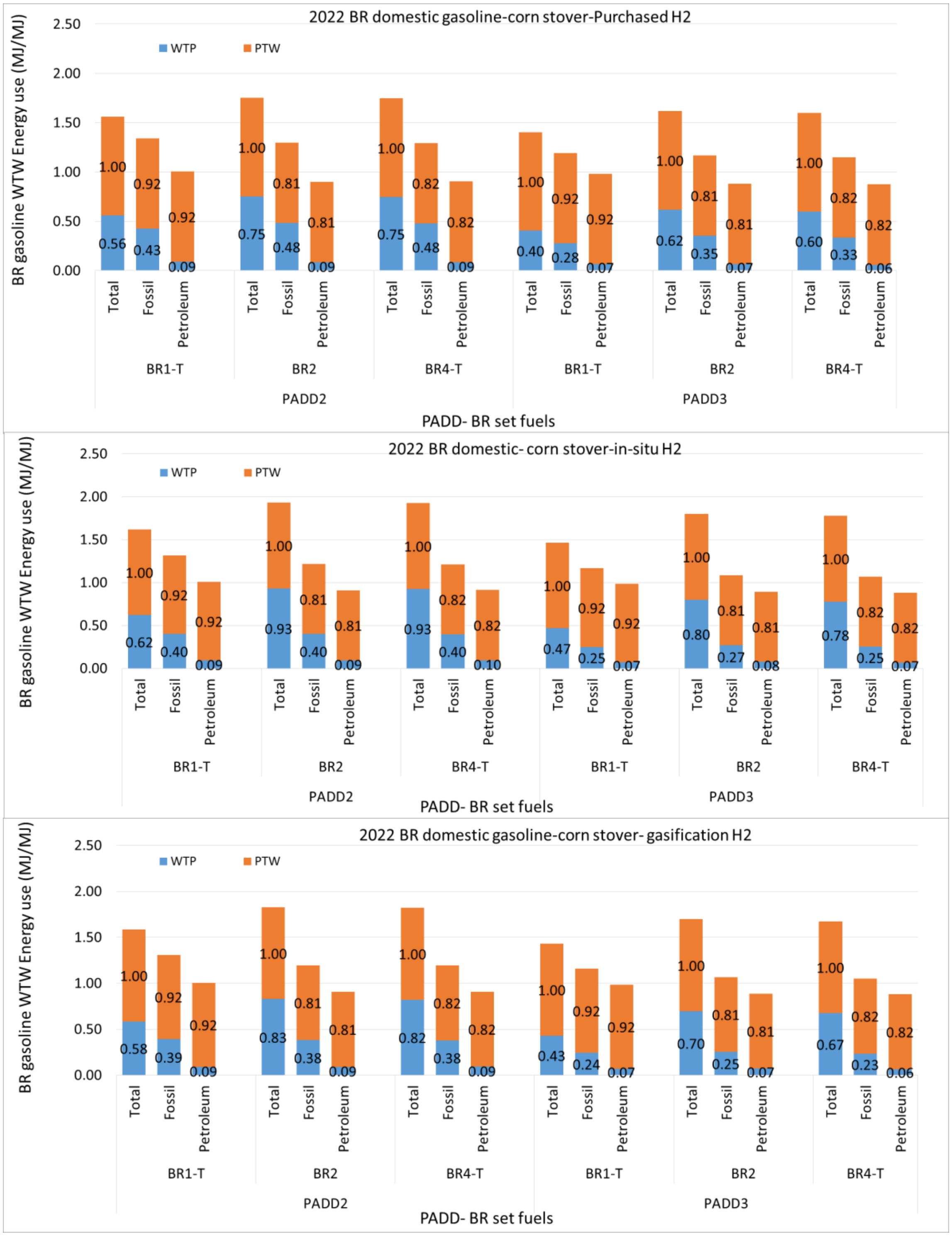


Figure 9-64. 2022 BR Set Domestic Finished Gasolines WTW Energy Uses with Ethanol from Corn Stover and Bioreformate Produced from Three Hydrogen Sources

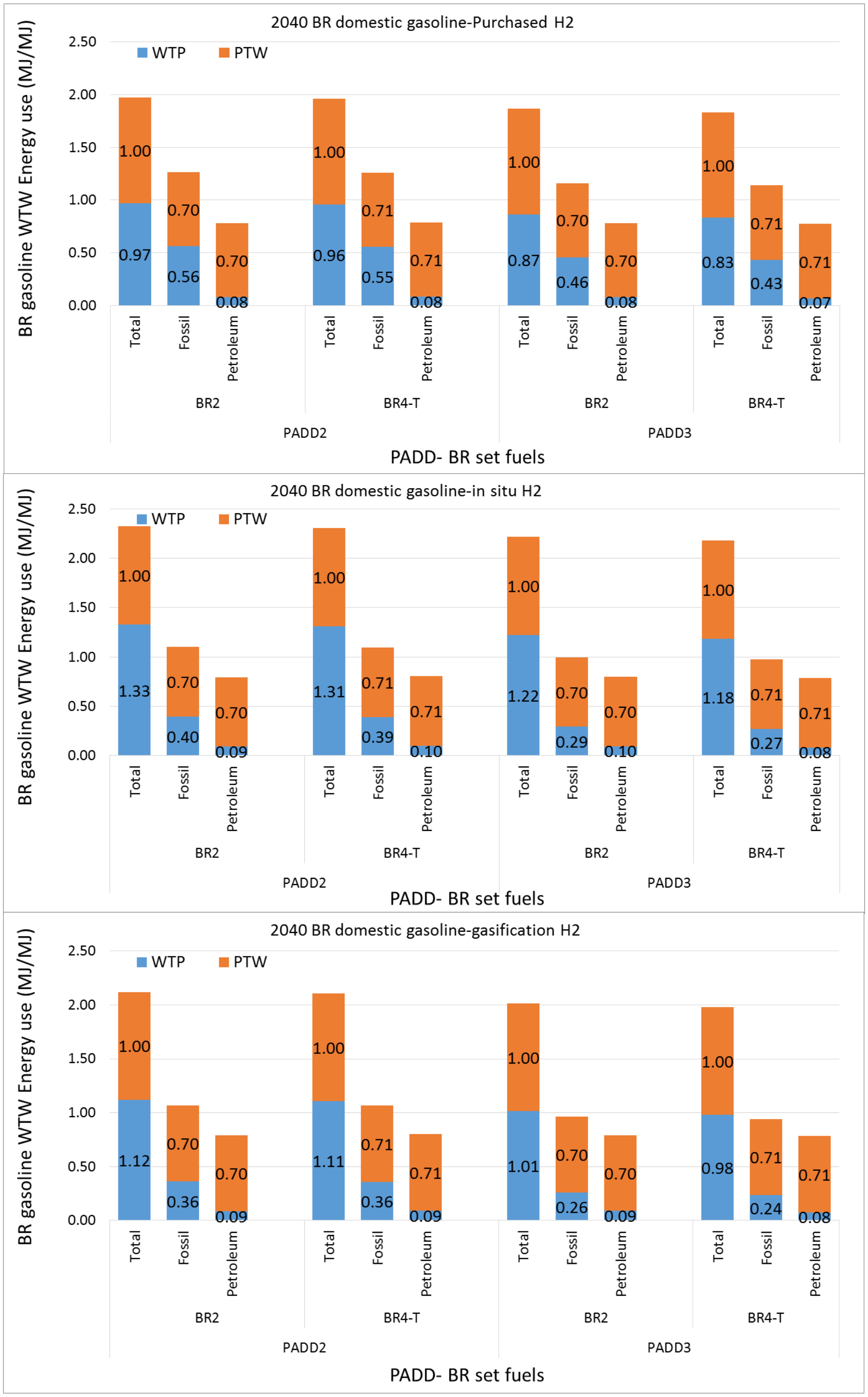


Figure 9-65. 2040 BR Set Domestic Finished Gasolines WTW Energy Uses with Bioreformate Produced from Three Hydrogen Sources

For each section of each figure, the relative trend of total, fossil and petroleum energy use among BR set domestic fuels remains the same, regardless of the ethanol source and BR production hydrogen supply.

Figure 9-66 and 9-67 show the differences in petroleum energy, NGC and renewable energy use among the six sets of 2022 results, and four sets of 2040 results (the four data bars at the right side). In the figures below, PD2 refers to PADD 2 and PD3 refers to PADD3.

In 2022, energy use for fuels with ethanol from corn stover (in the BAU gasoline) show higher total energy use and lower fossil energy use (0.01–0.02 MJ/MJ lower) compared with fuels with ethanol from corn starch. For each BR set fuel in 2022, the petroleum energy use is quite similar regardless of the PADD, BR bioreformate production hydrogen source, and ethanol source.

Among the three BR production processes, the total energy use increases in the order of purchased hydrogen < gasification hydrogen < in-situ hydrogen. Although the process with purchased hydrogen has the lowest total energy use, that energy use is mostly fossil energy, with an especially high amount of natural gas and coal. When all energy sources are included, the process with in-situ hydrogen has the highest total energy use, but it also has the highest percentage of energy from renewable sources (17.9-39.0%). Fossil energy use increases in the order of gasification hydrogen < in-situ hydrogen < purchased hydrogen, although the differences are only 0.04-0.09 MJ/MJ. All three processes have very similar petroleum energy usage.

In 2040, all domestic gasoline is HOF gasoline with BR bioreformate, thus, the energy uses do no change with ethanol source. The WTW energy uses of BR set gasolines in 2040 show a significant increase in total energy use over 2022, but also a significant increase in energy from renewable sources and a decrease in fossil energy use and petroleum energy use.

For each BR set fuel, BR from purchased hydrogen has the highest NGC energy use. In 2022, NGC (natural gas+coal) use reaches 16-27% for BR fuels produced in PADD 2 cases, and about 10-19% for PADD 3 cases. In 2040, the ratio reaches 13%–25% for PADD 2 cases and 8-20% for PADD 3 cases. This reveals how natural gas and coal (mostly natural gas) can play significant indirect roles in producing liquid transportation fuels, even though the major energy carrier is crude oil, a petroleum source. In contrast, the BR production processes with in-situ hydrogen and gasification hydrogen show much lower, but still significant use of NGC. In PADD3 the share of NGC use for both in-situ hydrogen and gasification is about 10-13% in 2022 and 8-9% for 2040. BR domestic production energy use, with various ethanol sources and hydrogen sources, compared with baselines is shown in Figures 9-68 and 9-69.

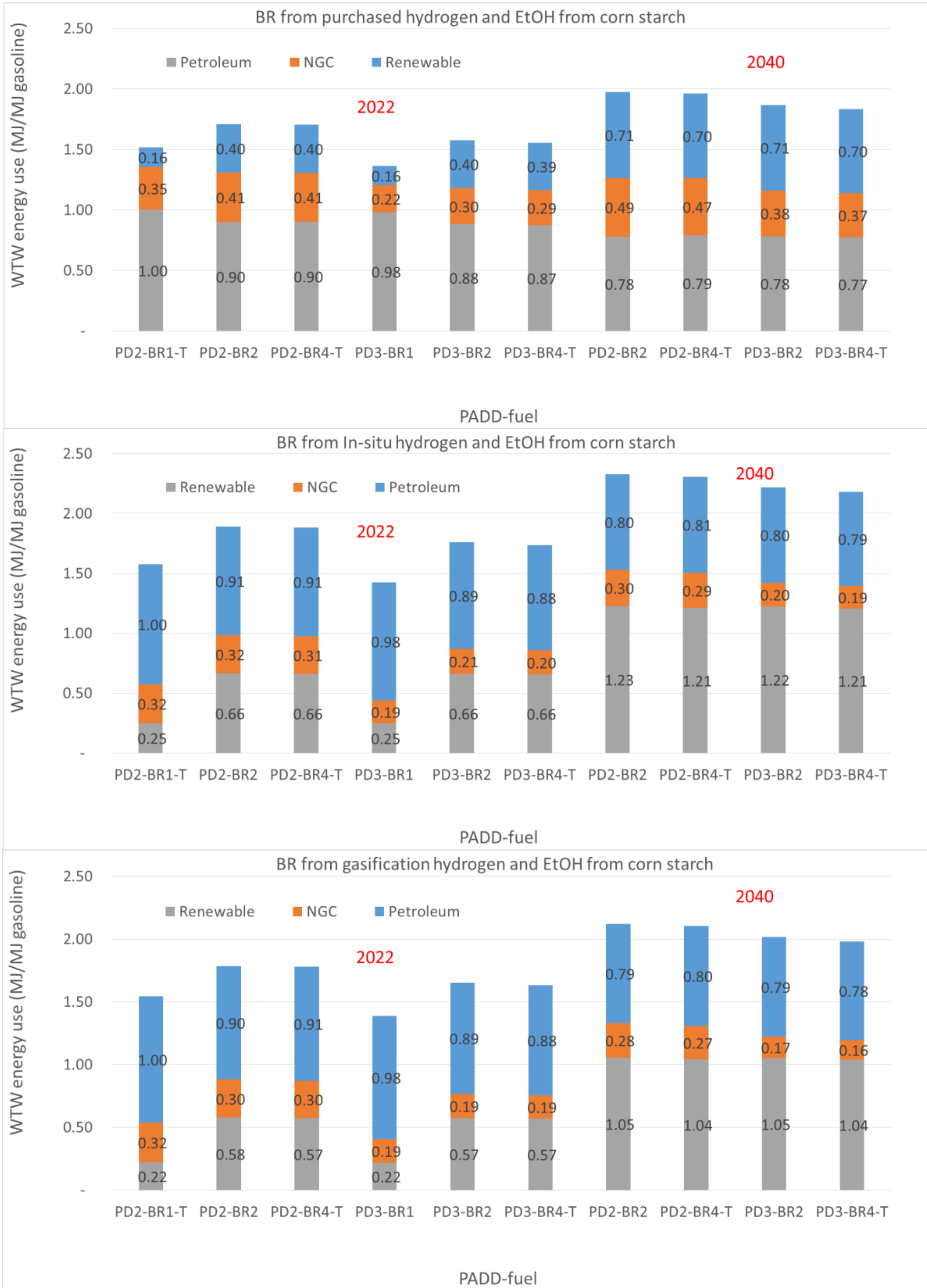


Figure 9-66. 2022 and 2040 WTW Energy Uses of BR Set Fuels Produced in PADD 2 and PADD 3 with Ethanol from Corn Starch and Bioreformate Produced with Different Hydrogen Sources

Figure 9-67. 2022 and 2040 WTW Energy Uses of BR Set Domestic Finished Gasolines Produced in PADD 2 and PADD 3 with Ethanol from Corn Stover and Bioreformate Produced with Different Hydrogen Sources

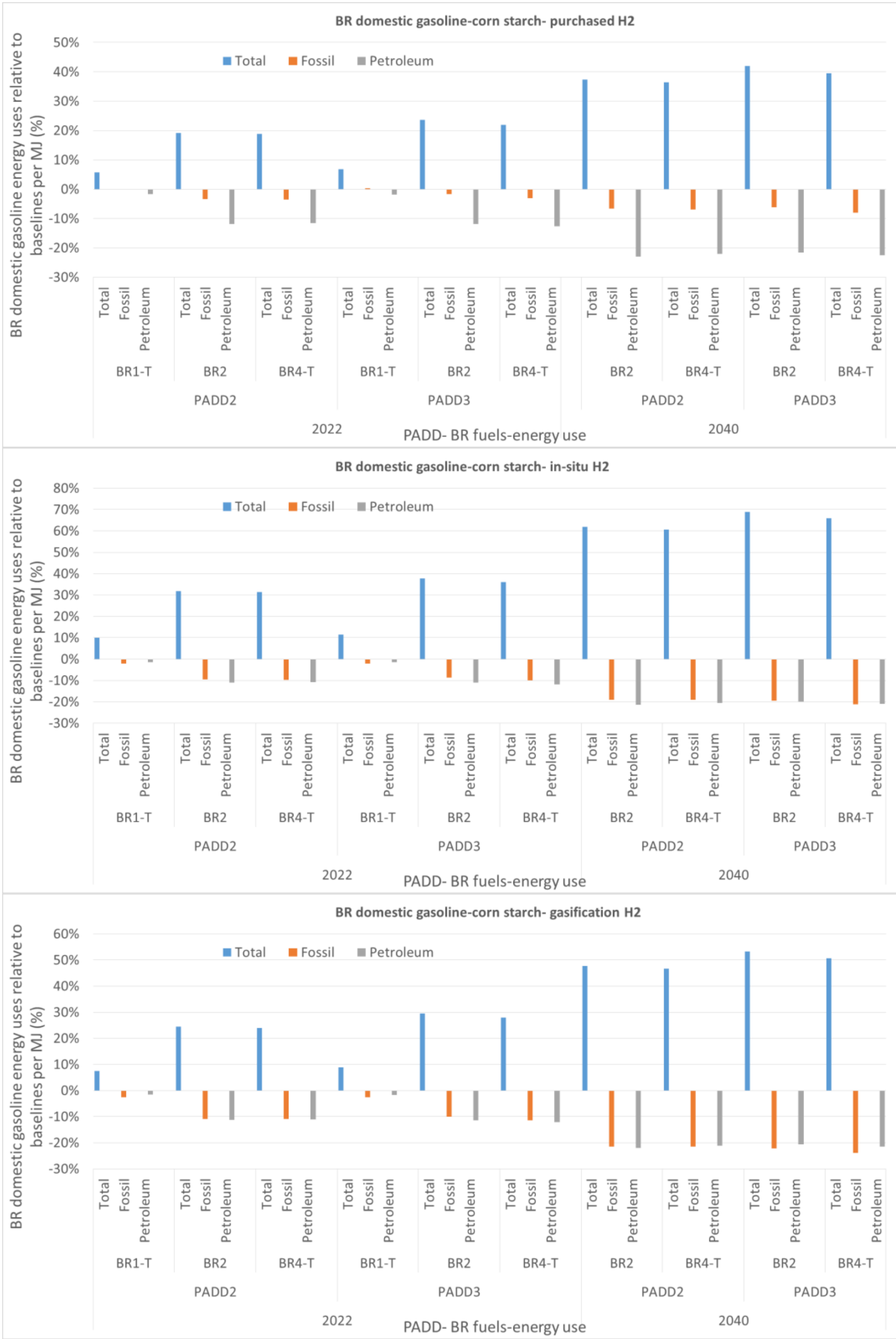


Figure 9-68. Per-MJ Changes of BR Domestic Finished Gasoline Energy Use Relative to Baselines. In 2022, BR Set BAU Gasolines and Baselines Have Corn Starch Ethanol. In 2040, BR Gasolines Have No Ethanol and Baselines Have Corn Starch Ethanol

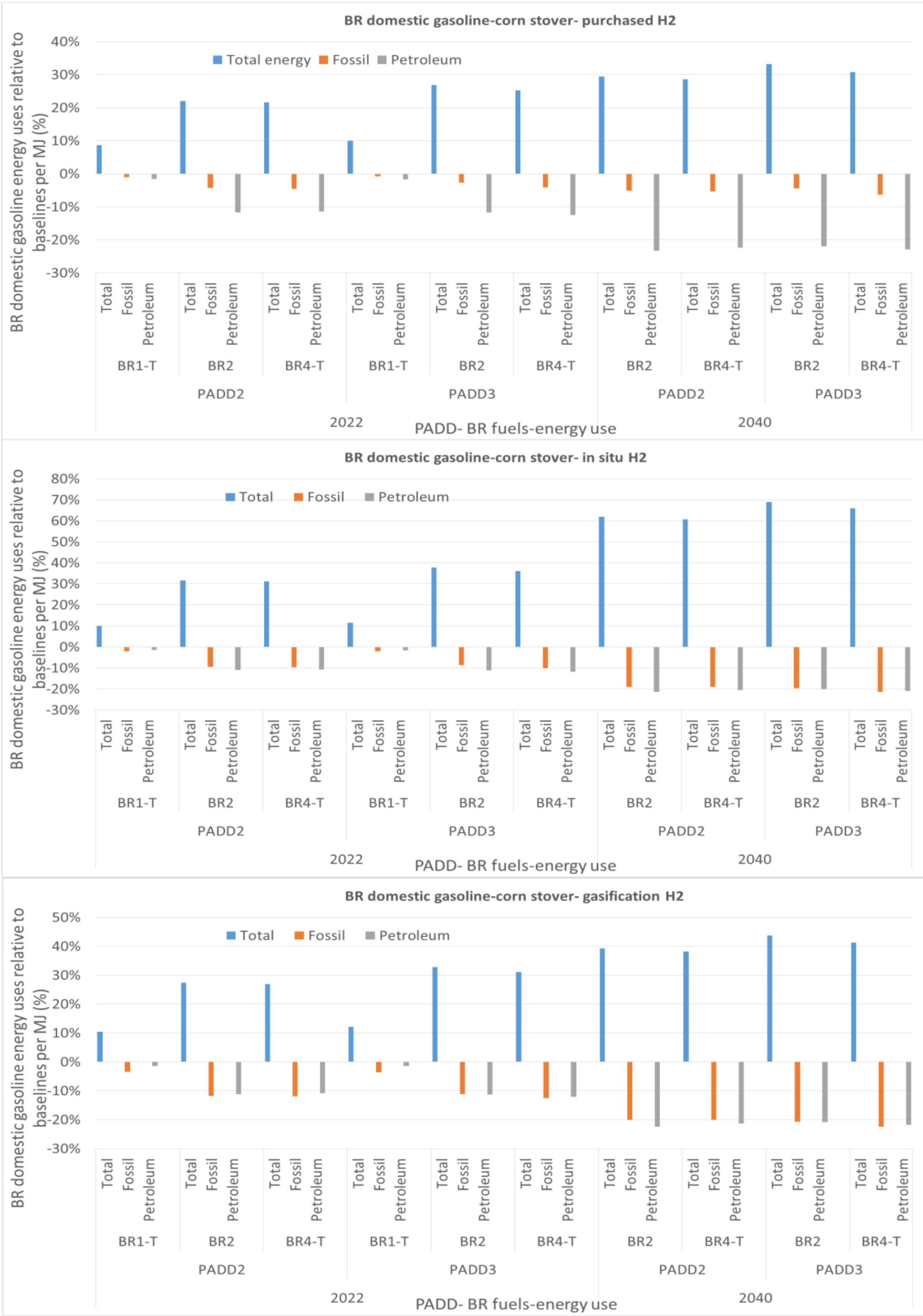


Figure 9-69. Per-MJ Changes of BR Domestic Finished Gasoline Energy Uses with Baselines. In 2022, BR Set BAU Gasolines have Corn Stover Ethanol and Baselines Have Corn Starch Ethanol. In 2040, BR Gasolines Have No Ethanol and Baselines Have Corn Stover Ethanol

In 2022, all BR set fuels' energy use, regardless of ethanol source and hydrogen source for BR bioreformate production, is compared to one set of baselines with corn starch ethanol. With only 10% ethanol blending in the BAU gasoline pool, the impact of ethanol source for BR energy use is relatively small. For all cases, BR fuels in PADD 3 show a greater increase in total energy use and a larger reduction in fossil energy use than in PADD 2.

The BR set gasolines with corn starch ethanol (in BAU gasoline pool) in 2022 show the following trends:

- BR domestic gasolines with purchased hydrogen: Total energy use is higher than baselines by 6% for BR1-T (9 vol% BR blending) and by 18-24% for BR2 and BR 4-T (27 vol. % bioreformate). However, their fossil energy use is reduced by 1%–3% and petroleum energy use is reduced by 1%–13%.

- BR domestic gasolines with in-situ hydrogen: Total energy use is higher than baselines by 10% for BR 1-T and 31%–38% for BR2 and BR4-T. However, fossil energy use of BR2 and BR4-T is reduced by 9-10%, and petroleum energy use is reduced by 11%–12%.

- BR domestic gasolines with gasification hydrogen: Total energy use is higher than baselines by 8-9% for BR1-T (9 vol% BR blending) and 24-30% for BR2 and BR 4-T. However, both fossil energy use and petroleum energy use for BR2 and BR4-T are reduced by 10%–12%.

The BR set gasolines with corn stover ethanol (in BAU gasoline pool) in 2022 show the following trends:

- BR domestic gasolines with purchased hydrogen: Total energy use is higher than baselines by 9% for BR 1 (9 vol% BR blending) and by 22%–27% for BR2 and BR 4-T (27 vol. % bioreformate). However, their fossil energy use is reduced by 1%–3% and petroleum energy use is reduced by 1%–13%.

- BR domestic gasolines with in-situ hydrogen: Total energy use is higher than baselines by 10%–15% for BR 1 and 30%–38% for BR2 and BR 4. However, fossil energy use of BR2 and BR4-T is reduced by 10%–11%, and petroleum energy use is reduced by 11%.

- BR domestic gasolines with gasification hydrogen: Total energy use is higher than baselines by 10%–12% for BR1-T (9 vol% BR blending) and 27%–33% for BR2 and BR 4-T. However, both fossil energy use and petroleum energy use for BR2 and BR4-T are reduced by 11%–12%.

In 2040, two sets of baselines are used: one with corn starch ethanol and the other with corn stover ethanol. All cases show greater energy use reduction than in 2022. The cases with purchased hydrogen show fossil energy use reduction by 4-5% and petroleum energy use reduction by 22%. Cases with in-situ hydrogen and gasification hydrogen saw both fossil and petroleum energy use reduction by about 22%.

9.2.1.2 Per-MJ BR Fuel WTW GHG Emissions in Two PADDs

The exported gasoline GHG burdens are small and were added back to HOF WTP GHG emissions. The exported gasoline burden that is shifted back to the BR domestic gasolines is shown in Table 9-13 below.

Table 9-13. Exported Gasoline GHG Burden to HOF Gasoline (g/MJ HOF)

		BR1-T	0.00
2022	PADD 2	BR2	0.00
		BR4-T	0.00
2022	PADD 3	BR1	0.00
		BR2	0.00
		BR4-T	0.00
2040	PADD 2	BR2	1.09
		BR4-T	1.74
2040	PADD 3	BR2	0.00
		BR4-T	0.32

In 2022, BR set domestic gasoline has both BAU gasoline and HOF gasoline. The WTW GHG emissions of the former varies with ethanol source and the latter varies with BR production H_2 source. The WTW GHG emissions of the BAU and HOF gasolines are shown in Figures 9-70 and 9-71.

Along the WTW life cycle, HOF gasoline has lower GHG emissions than BAU gasoline, due to their general higher bio-content, which produces biogenic CO_2. Even for BR1-T set fuel, its HOF gasoline has 9% bioreformate, still shows lower GHG emissions than its BAU gasoline with 10% ethanol, owing to the higher bio-carbon content in the former as bioreformate has no oxygen. The WTW GHG emissions of the resulting BR set domestic gasoline pools for 2022 and 2040 are shown in Figures 9-72, 9-73, and 9-74.

As expected, the BR set fuels produced in PADD 2 have higher GHG emissions than their counterparts produced in PADD 3 (about 10% higher). For each BR set, the domestic gasoline produced with purchased hydrogen has the highest GHG emissions, followed by the process with in-situ hydrogen and then gasification hydrogen. The differences among these three hydrogen sources are greater for BR2 and BR4-T fuels that have higher percentage of bioreformate than BR1-T. The difference between fuels with corn starch ethanol and corn stover ethanol are small, since only 10% ethanol is blended in half of the domestic gasoline pool.

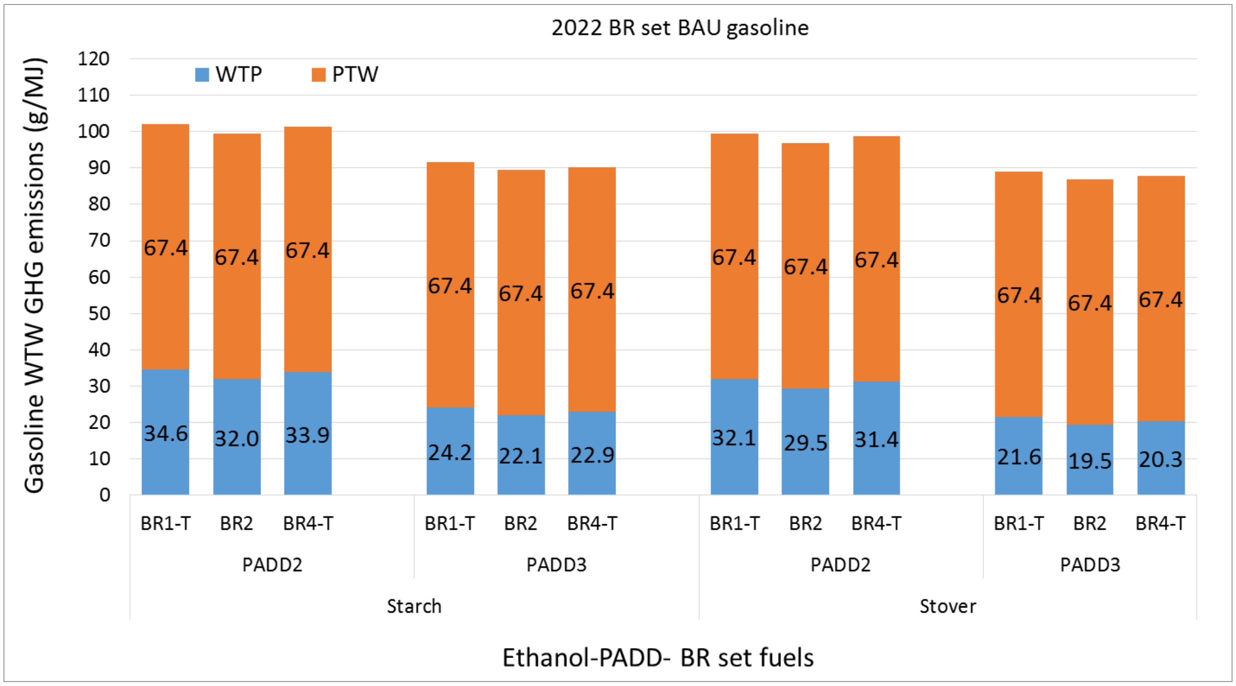


Figure 9-70. WTW GHG Emissions of BR Set BAU Gasoline in 2022 Broken Down by WTP and PTW

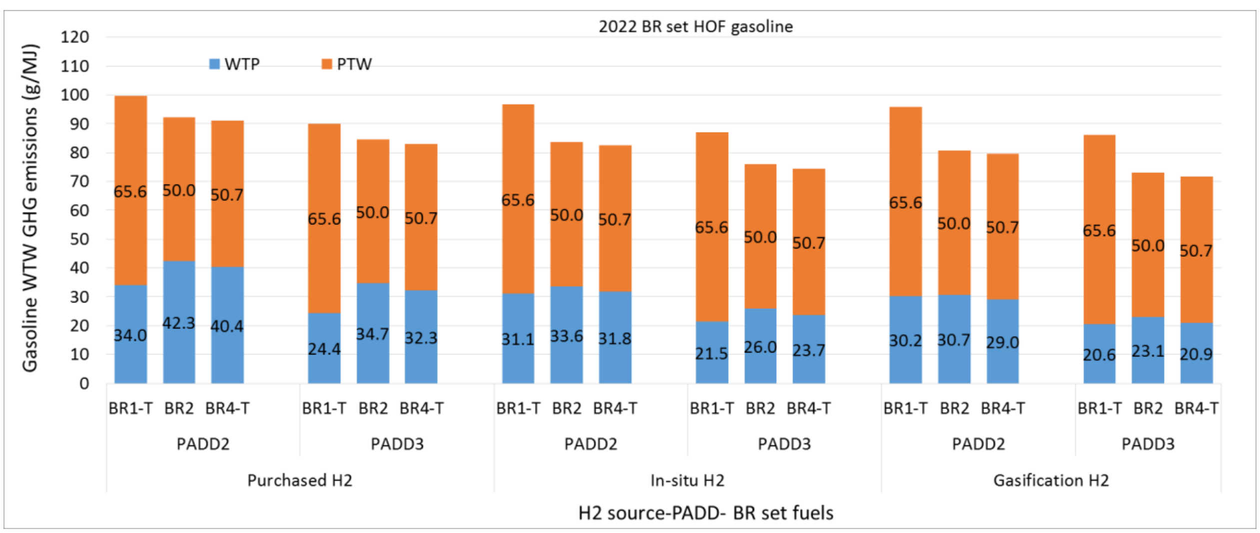


Figure 9-71. WTW GHG Emissions of BR Set HOF Gasolines in 2022 with Three Hydrogen Sources for BR Production

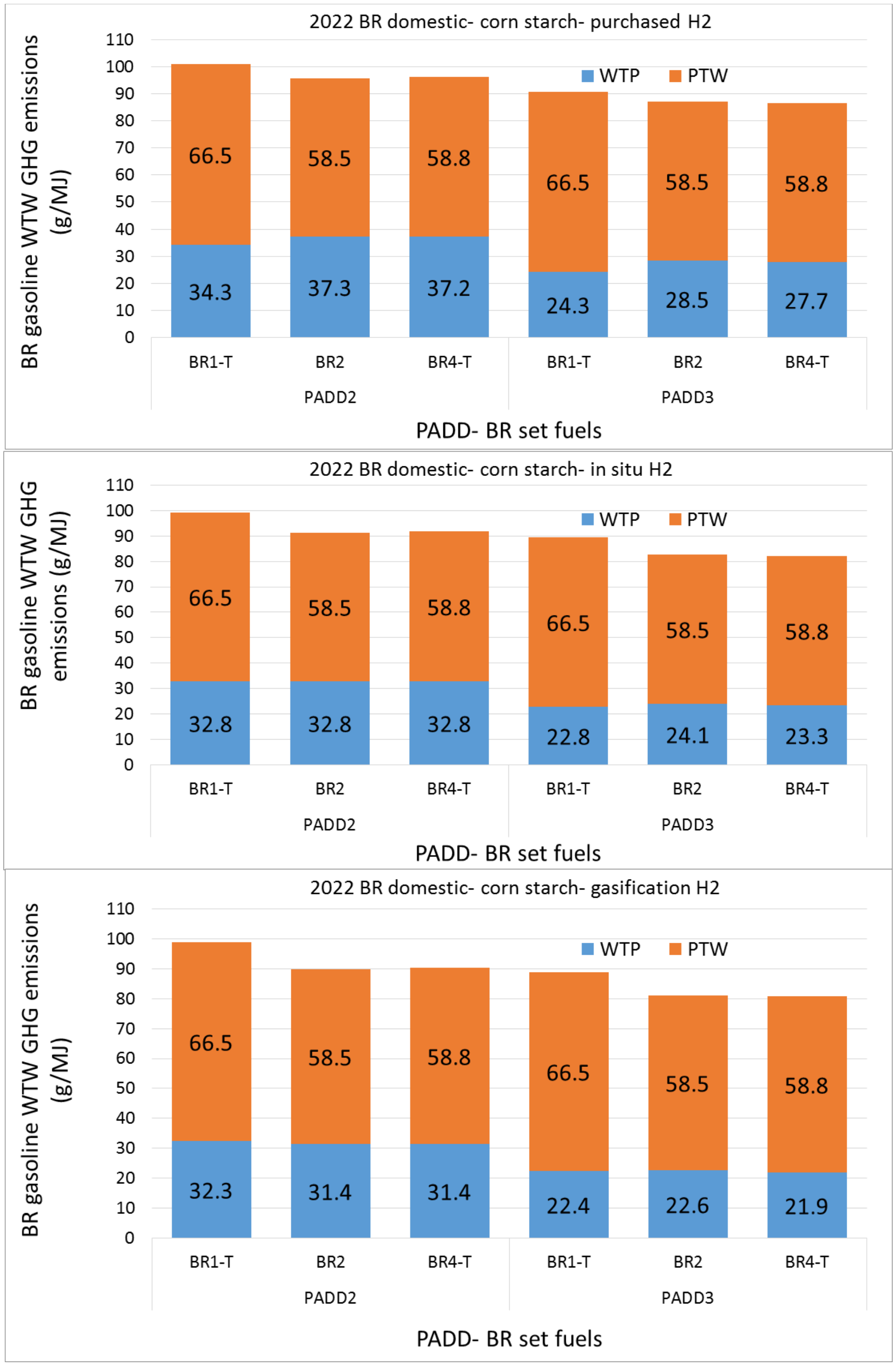


Figure 9-72. WTW GHG Emissions (g/MJ) of BR Set Domestic Finished Gasolines in 2022 with Corn Starch Ethanol in BAU Gasoline Pool and Three Different Hydrogen Sources for BR Production

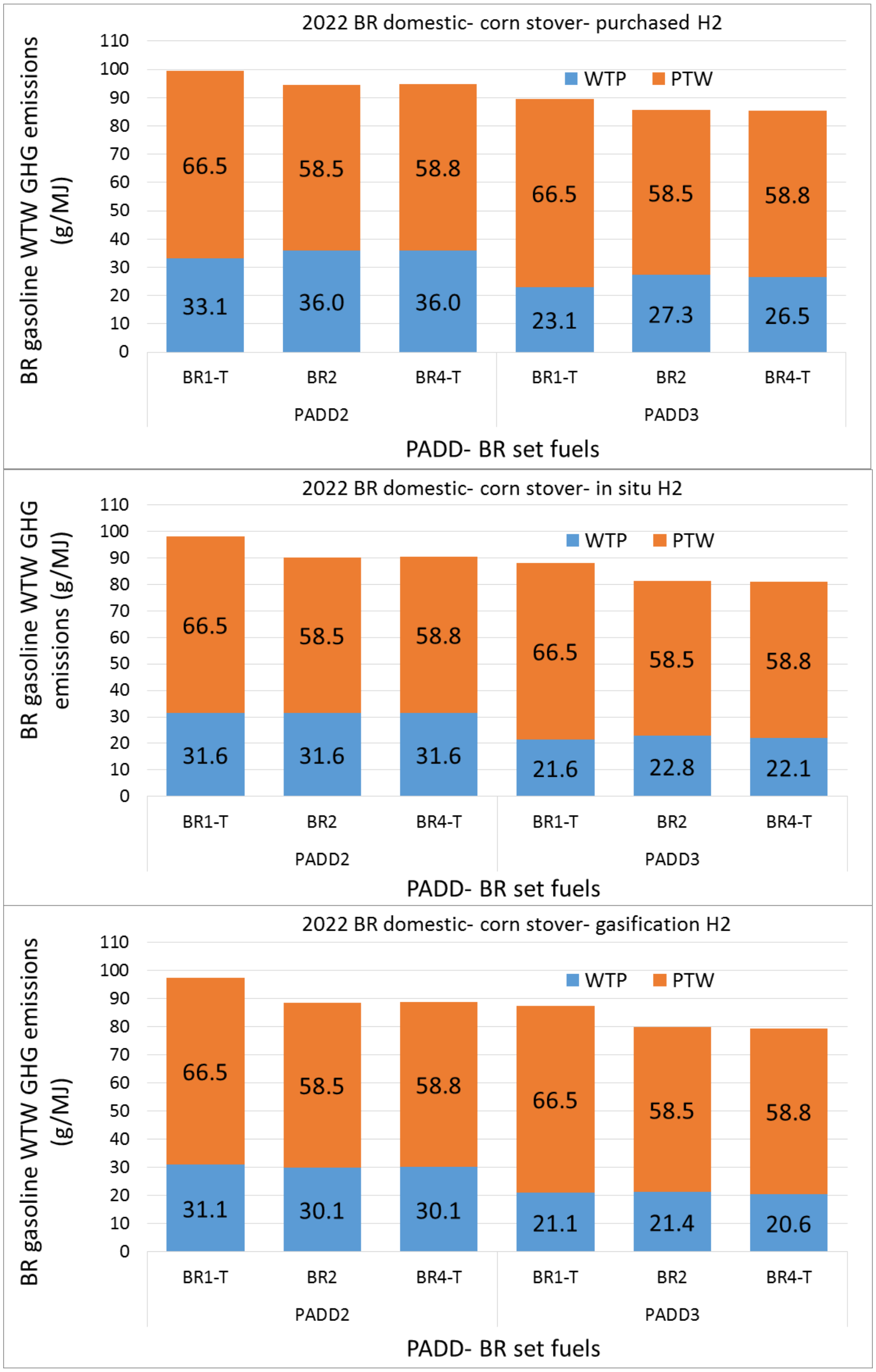


Figure 9-73. WTW GHG Emissions (g/MJ) of BR Set Domestic Finished Gasolines in 2022 with Corn Stover Ethanol in BAU Gasoline Pool and Three Different Hydrogen Sources for BR Production

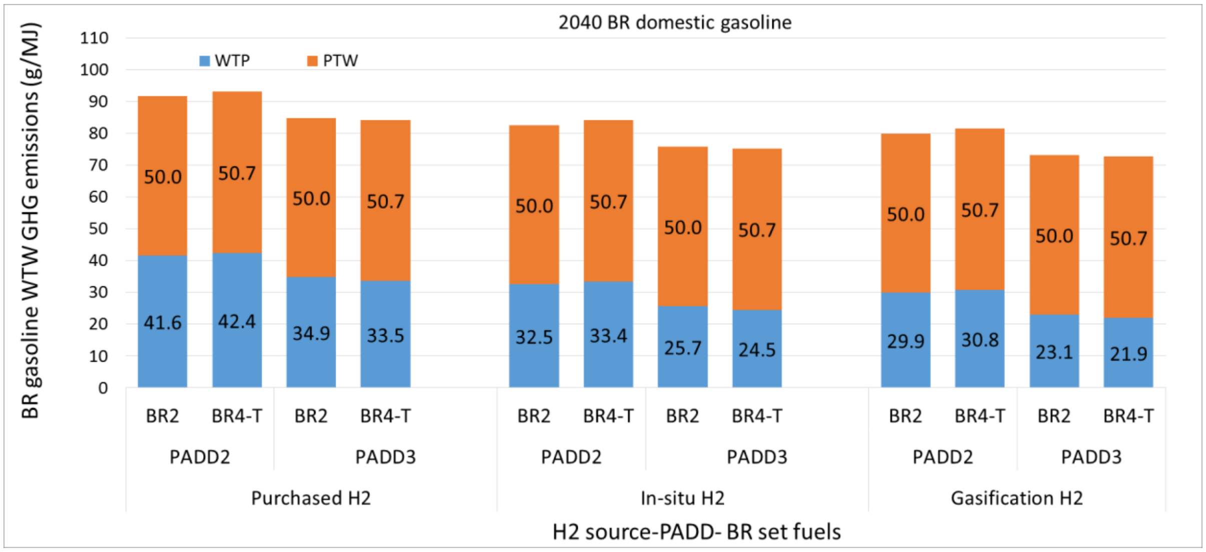


Figure 9-74. WTW GHG Emissions of BR Set Fuels in 2040 (g/MJ) with Three Different Hydrogen Sources for Bioreformate Production

In 2040, with 100% HOF share, the differences in WTW GHG emissions among the three BR hydrogen sources increases to over 10 g/MJ. With similar petroleum energy use for all three, the differences in GHG emissions are mostly attributable to the different natural gas and coal uses, especially natural gas use for hydrogen production.

A comparison of BR set domestic finished gasoline pool WTW GHG emissions with baselines is shown in Figure 9-75 for 2022 and Figure 9-76 for 2040. Although ethanol is not used in the 2040 BR set fuels, it is used in the baseline fuels so comparisons are made relative to both corn starch and corn stover baseline fuels.

In 2022, both BR2 and BR4-T have larger reductions in GHG emissions compared with E10 baseline with corn starch and corn stover ethanol than BR1 does, Regardless of PADD. As expected, BR fuels produced with gasification hydrogen show greatest GHG emissions reduction, reaching 12%.

In 2040, with 100% HOF gasoline, using BR set fuels produced with gasification hydrogen can reduce WTW GHG emissions by about 20%. Changes in BR WTW GHG emissions as compared with baselines are similar among different PADD refineries and for different BR set fuels.

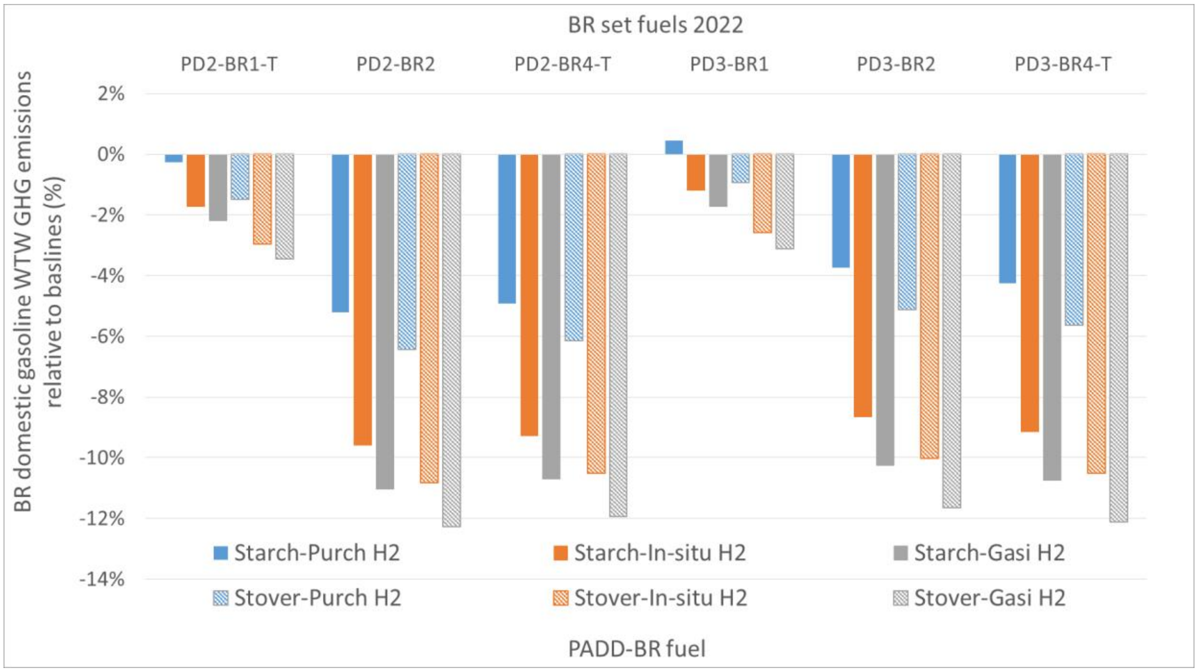


Figure 9-75. Per-MJ Changes of BR Domestic Finished Gasoline (BAU Gasolines with Corn Starch Ethanol and Corn Stove Ethanol) WTW GHG Emissions Relative to Baselines in 2022. Baselines Use Corn Starch Ethanol

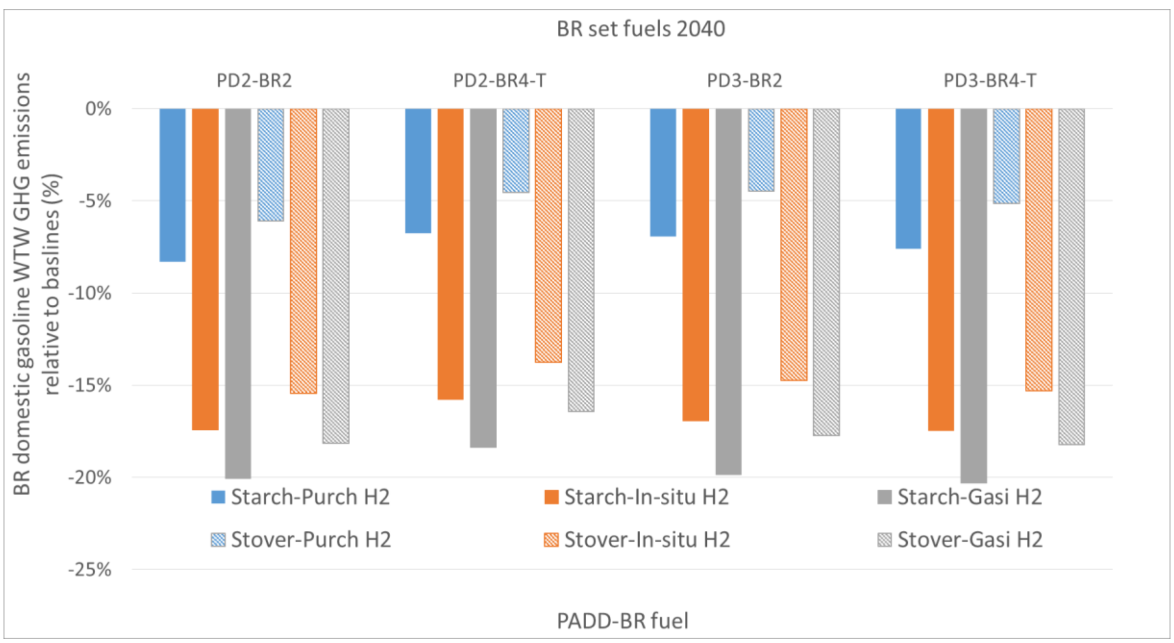


Figure 9-76. Per-MJ Changes of BR Domestic Finished Gasolines (No Ethanol) WTW GHG Emissions with Baselines in 2040. Baselines Use Corn Starch Ethanol and Corn Stover Ethanol, Respectively

9.2.1.3 Per-Mile BR Fuels WTW Energy Use in Two PADDs

The WTW energy use for BR gasolines in aggregate refineries on a per-mile basis are presented here. In 2022, energy use for BAU gasoline varies with ethanol source and energy use for HOF gasoline varies with hydrogen source. Their figures are shown in Figure 9-77 and Figure 9-78, broken down into WTP and PTW stages. The PTW energy use values for the BAU gasoline is based on the engine efficiencies and fuel economies obtained in the engine testing and vehicle simulation portions of this U.S.DRIVE study.

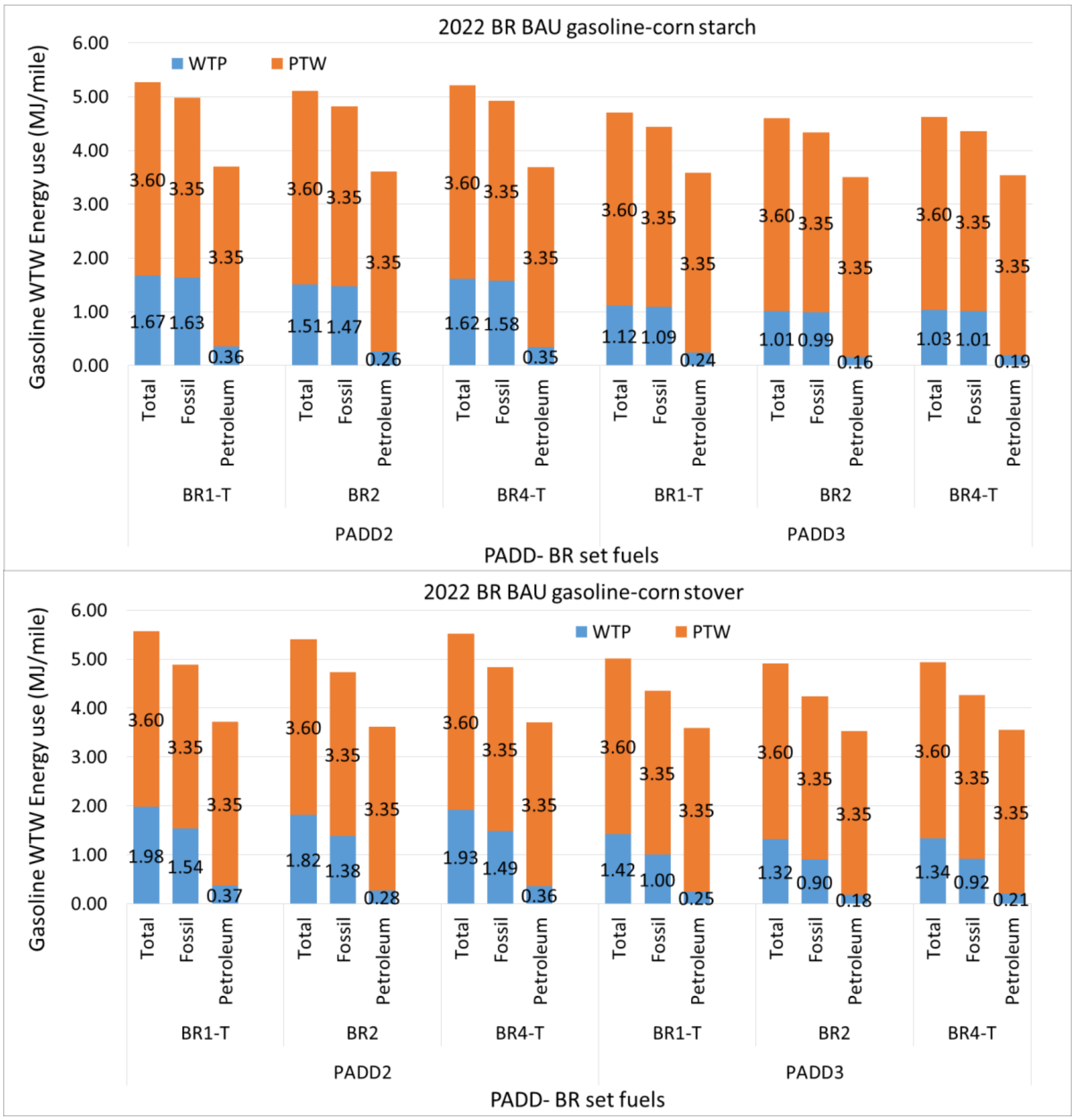


Figure 9-77. Per-Mile WTW Energy Uses of BR BAU Gasoline in 2022 with Corn Starch and Corn Stover Ethanol

As discussed before, the BR produced in PADD 2 shows higher energy use than that in PADD 3, because of higher energy use in the feedstock WTP stage. The BR BAU gasolines with corn starch ethanol have higher fossil energy use than those with corn stover ethanol. For a given ethanol source, the differences in energy use among different BR BAU gasolines are small. This is because the BAU gasolines all contain only 10% ethanol, so their WTP energy use is based on BOB production energy use, which in turn is determined mostly by refinery type, not by fuel properties, as discussed in Section 7.

Energy use for BR HOF gasoline varies greatly with hydrogen source, PADD refinery, and BR fuel, as shown in Figure 9-78. Again, the BR HOF gasolines with gasification H_2 have the lowest fossil energy use. The lowest fossil energy use is observed for BR4-T with gasification hydrogen produced in a PADD 3 refinery. The energy uses for HOF gasoline with ON/CR of 3.0, 3.7 and 5.6 are shown in Appendix 4 in Table A4-22. A4-23 and A4-24, respectively for year 2022. Per-mile energy use for BR HOF gasoline with ON/CR of 3.7 and 5.6 is more than with a 3.0 ON/CR assumption, but the difference is very small (0.07 MJ/mile or less).

The combined BR domestic gasoline energy use for 2022 and 2040, with the fuel economy based on ON/CR of 3.0, is shown in Figures 9-78 through 9-81. The HOF results in 2040 are shown as results of domestic gasoline pool, since 100% HOF share is assumed in 2040.

The energy uses for BR domestic gasoline in 2022 and in 2040 are also shown in Appendix 4 in Tables A4-25 through A4-28.

The per-mile energy use shows patterns similar to per-MJ energy use, with differences relating to differences in fuel economy gain enabled by the different fuels. The impact of the BR production hydrogen source on energy use is significant, and the delta between hydrogen sources is as high as 0.70 MJ/mile. The bioreformate blending level has the greatest impact (i.e., a delta as high as 1.2 MJ/mile exists between the BR1-T and BR2 values). The delta between corn starch and stover is about 0.15 MJ/mile, since only 5 vol% ethanol is present in the domestic gasoline pool (10% ethanol in BAU gasoline, which is 50 vol% of domestic gasoline pool).

Energy use results for the BR domestic gasoline pool in 2022 with fuel economies derived from ON/CR of 3.7 and 5.6 are similar and are shown in Tables A4-25 through A4-27. The ON/CR ratio has negligible impact on the total and PTW energy use per mile.

Energy use results for BR domestic gasolines are compared to baselines in Figures 9-82 and 9-83 for year 2022 and 2040. For 2022, the BR domestic gasoline pool contains ethanol in BAU gasoline pool and ethanol can be sourced from either corn starch or corn stover, however, they are compared to the same set of E10 baselines with corn starch ethanol. For 2040, the BR domestic gasolines do not include ethanol; however, they are compared to dual baselines with corn starch ethanol or corn stover ethanol, respectively. In other words, in 2022, the BR domestic gasoline energy uses vary with ethanol source, but use a single set of baselines with corn starch ethanol, thus the difference in BR domestic finished gasolines energy uses versus baselines vary with ethanol sources. In 2040, the BR domestic finished gasolines energy uses do not change with ethanol sources, but the baseline energy uses vary with it, thus the changes of BR domestic gasoline energy uses to baselines still vary with ethanol sources.

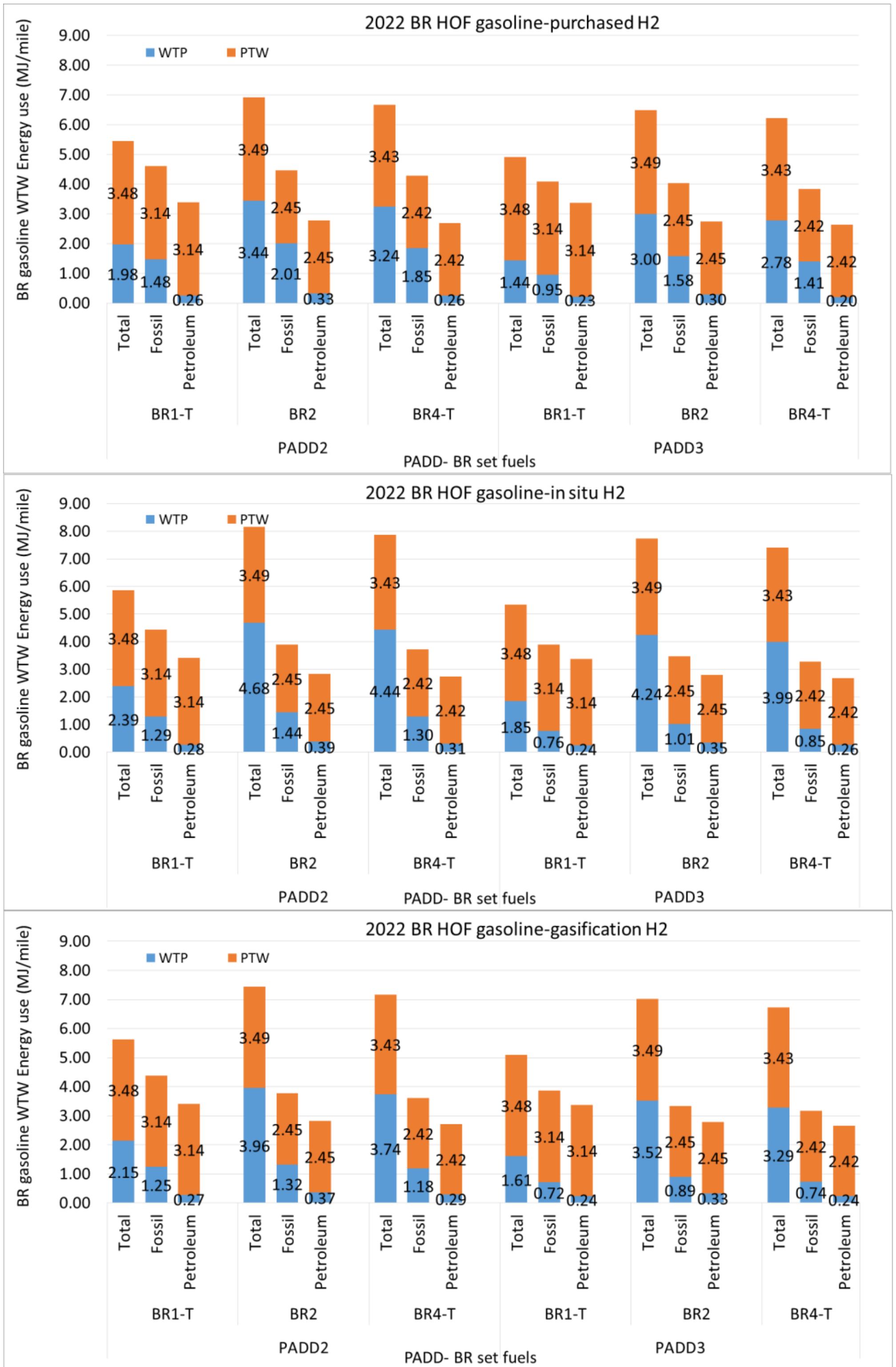


Figure 9-78. Per-Mile WTW Energy Use of BR Set HOF Gasoline Pool in 2022 with Different Hydrogen Sources for BR Production (for ON/CR of 3.0)

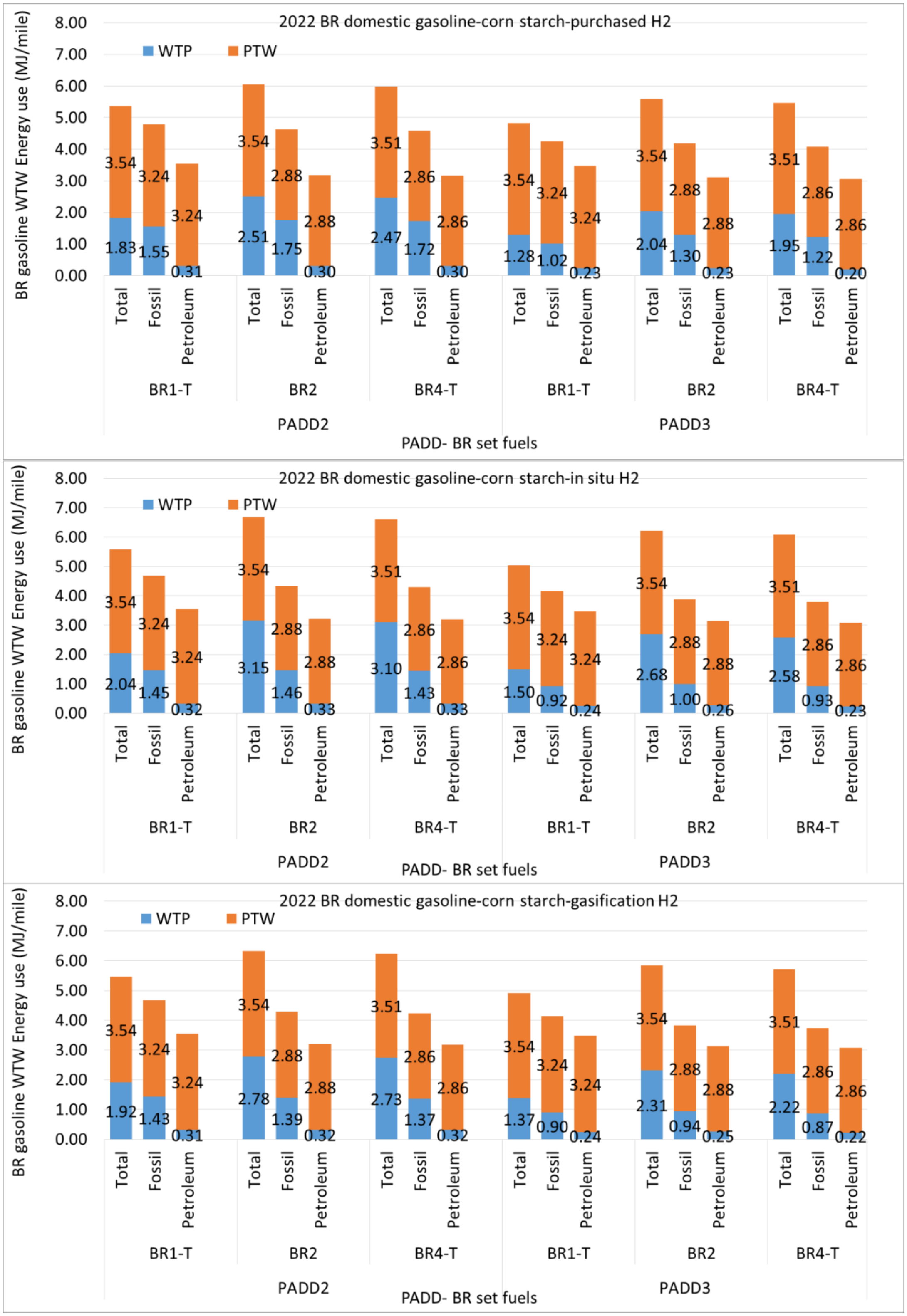


Figure 9-79. Per-Mile WTW Energy Uses of BR Set Domestic Gasolines in 2022 with Corn Starch Ethanol in BAU Gasoline Pool and Different Hydrogen Sources for BR Production (for ON/CR of 3.0)

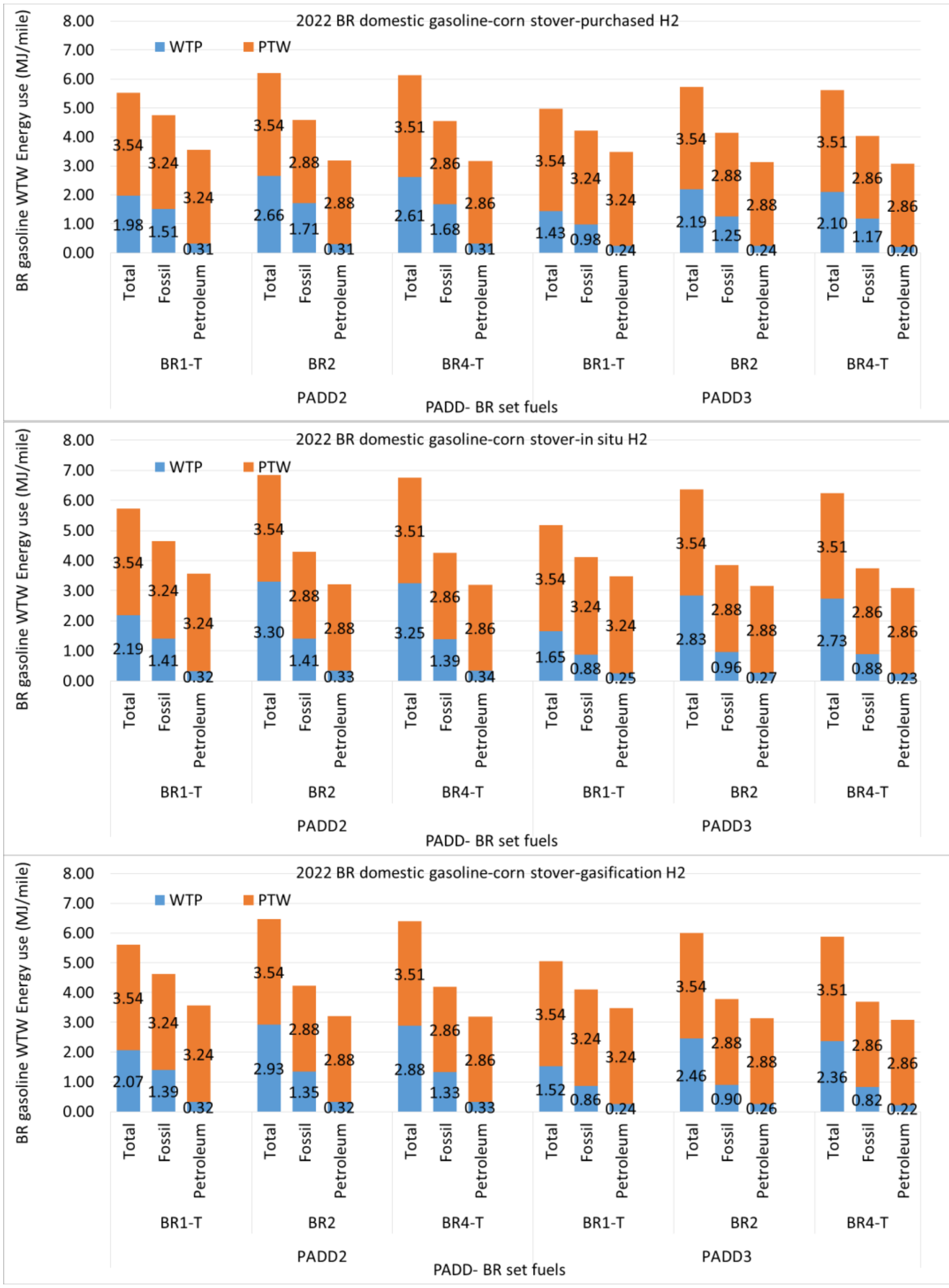


Figure 9-80. Per-Mile WTW Energy Use of BR Domestic Finished Gasolines in 2022 with Corn Stover Ethanol in BAU Gasoline Pool and Different Hydrogen Sources for BR Production (for ON/CR of 3.0)

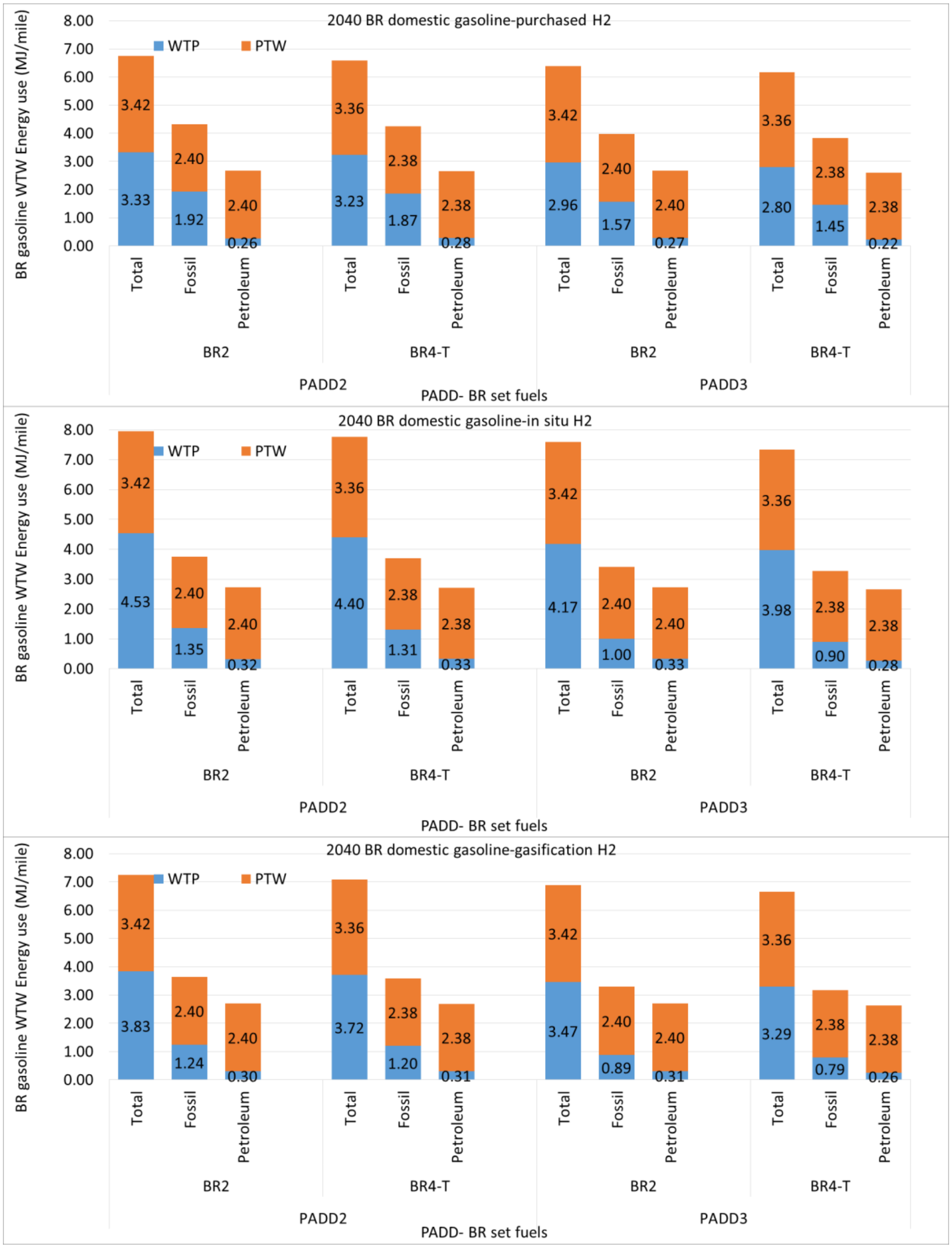


Figure 9-81. Per-Mile WTW Energy Use of BR Domestic Finished Gasolines in 2040 with Different Hydrogen Sources for BR Production (for ON/CR of 3.0)

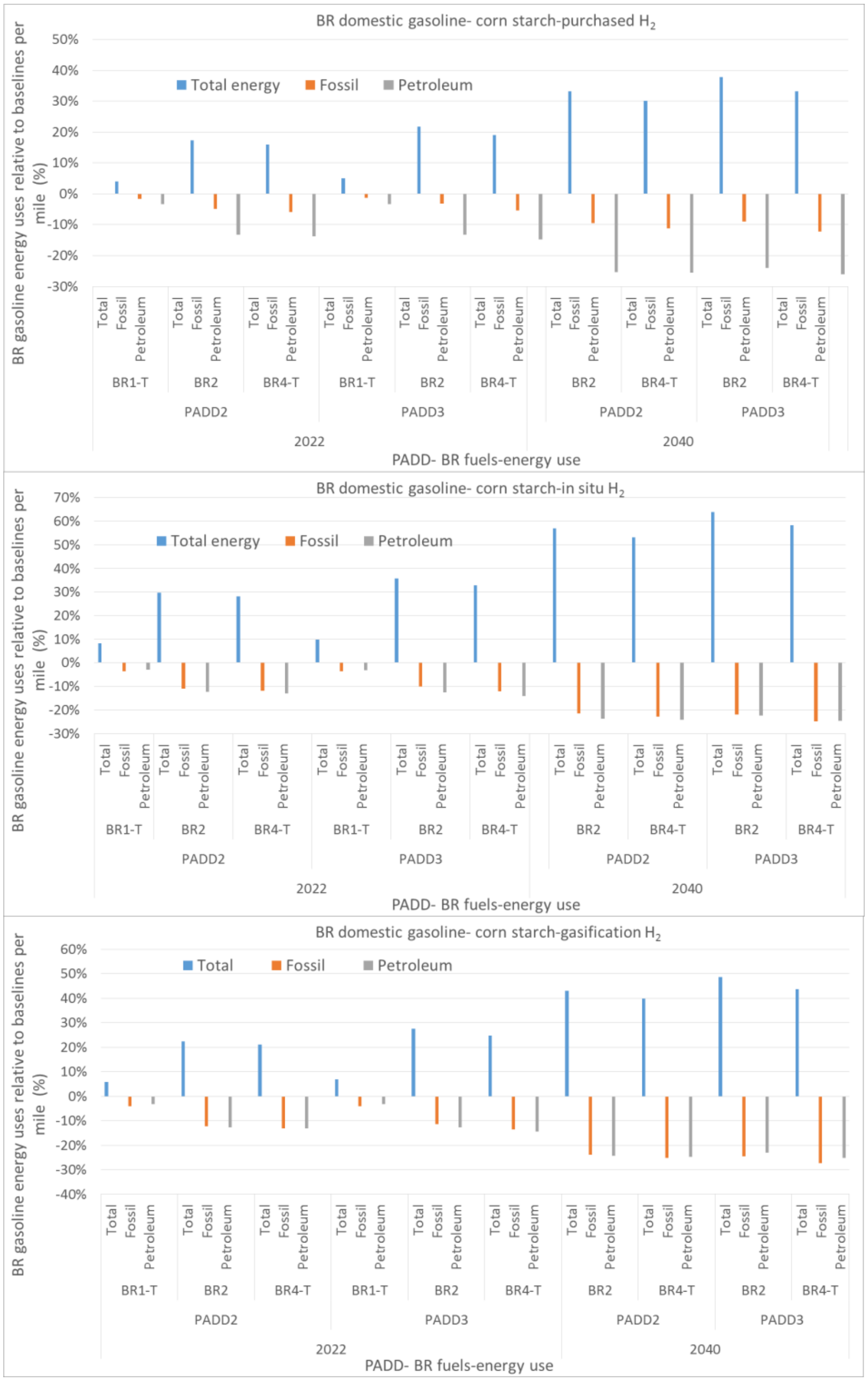


Figure 9-82. Per-Mile Changes of BR Domestic Finished Gasolines WTW Energy Use with Baselines with Different Hydrogen Sources for BR Production (for ON/CR of 3.0). In 2022, BAU Gasolines and Baselines Use Corn Starch Ethanol. In 2040, BR Gasolines Have No Ethanol and Baselines Use Corn Starch Ethanol

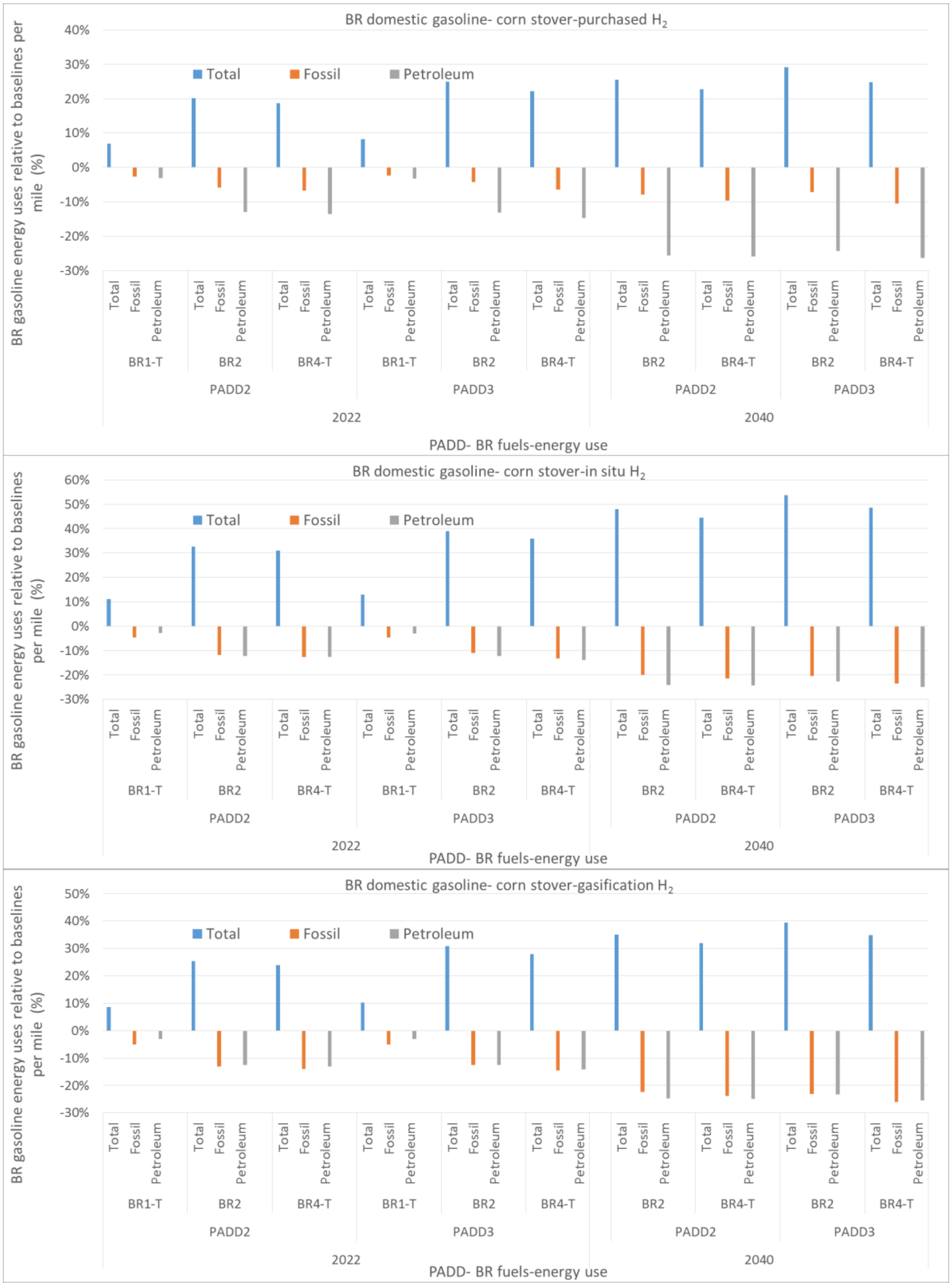


Figure 9-83. Per-Mile Changes of BR Domestic Finished Gasolines WTW Energy Use with Baselines with Different Hydrogen Sources for BR Production (for ON/CR of 3.0). In 2022, BAU Gasolines Use Corn Stover Ethanol and Baselines Use Corn Starch Ethanol. In 2040, BR Gasolines Have No Ethanol and Baselines Use Corn Stover Ethanol

Per-mile energy use for the BR gasoline pools with corn starch ethanol in BAU gasoline in 2022 show the following trends:

- BR domestic gasolines with purchased hydrogen produced in PADD 2 and PADD 3 refineries: Total energy use is higher than baselines by 5-6% for BR1-T (9 vol% BR blending) and 17%–22% for BR2 and BR4-T. However, BR2 and BR4-T fossil energy use is reduced by 2%–5%, and petroleum energy use is reduced by 13%–14%.

- BR domestic gasolines with in-situ hydrogen: Total energy use is higher than baselines by 10% for BR1-T (9 vol% BR blending) and 30-37% for BR2 and BR4-T. However, BR2 and BR4-T fossil energy use is reduced by 9-11%, and petroleum energy use is reduced by 11%–13%.

- BR domestic gasolines with gasification hydrogen: Total energy use is higher than baselines by 7%–8% for BR1-T (9 vol% BR blending) and 22%–28% for BR2 and BR4-T. However, BR2 and BR4-T fossil energy use and petroleum energy use are reduced by 12%–14%.

The results assuming corn stover ethanol in BAU gasoline are similar, but with a slight increase in total energy and a slight decrease in fossil and petroleum energy use.

In 2040, all the cases show larger energy use changes than in 2022. Fuels made with purchased hydrogen show fossil energy use reductions of 8-11%, and petroleum energy use reductions of 23%–25%. For fuels made with in-situ hydrogen, both fossil and petroleum energy use was reduced by 20%–23%. Fuels made with gasification hydrogen showed both fossil and petroleum energy use reduced by 23%–26%. Thus the BR domestic gasolines with purchased hydrogen show the least fossil energy use reduction, but the highest petroleum energy reduction. The BR domestic gasolines with gasification hydrogen show greatest fossil energy use reduction.

BR energy use on a per-mile basis shows greater reductions than on a per-MJ basis, by taking into account fuel economy gains enabled by use of hydrocarbon bio-components with higher octane numbers.

Changes in BR domestic gasoline energy use as compared with baselines with projected fuel economies for ON/CR of 3.7 and 5.6 are similar to those based on 3.0 ON/CR, and so are not shown here for brevity.

9.2.1.4 Per-Mile BR Fuel WTW GHG Emissions in Two PADD

The WTW GHG emissions of the BR set fuels on a per-mile basis are shown in Figures 9-84 through 9-88.

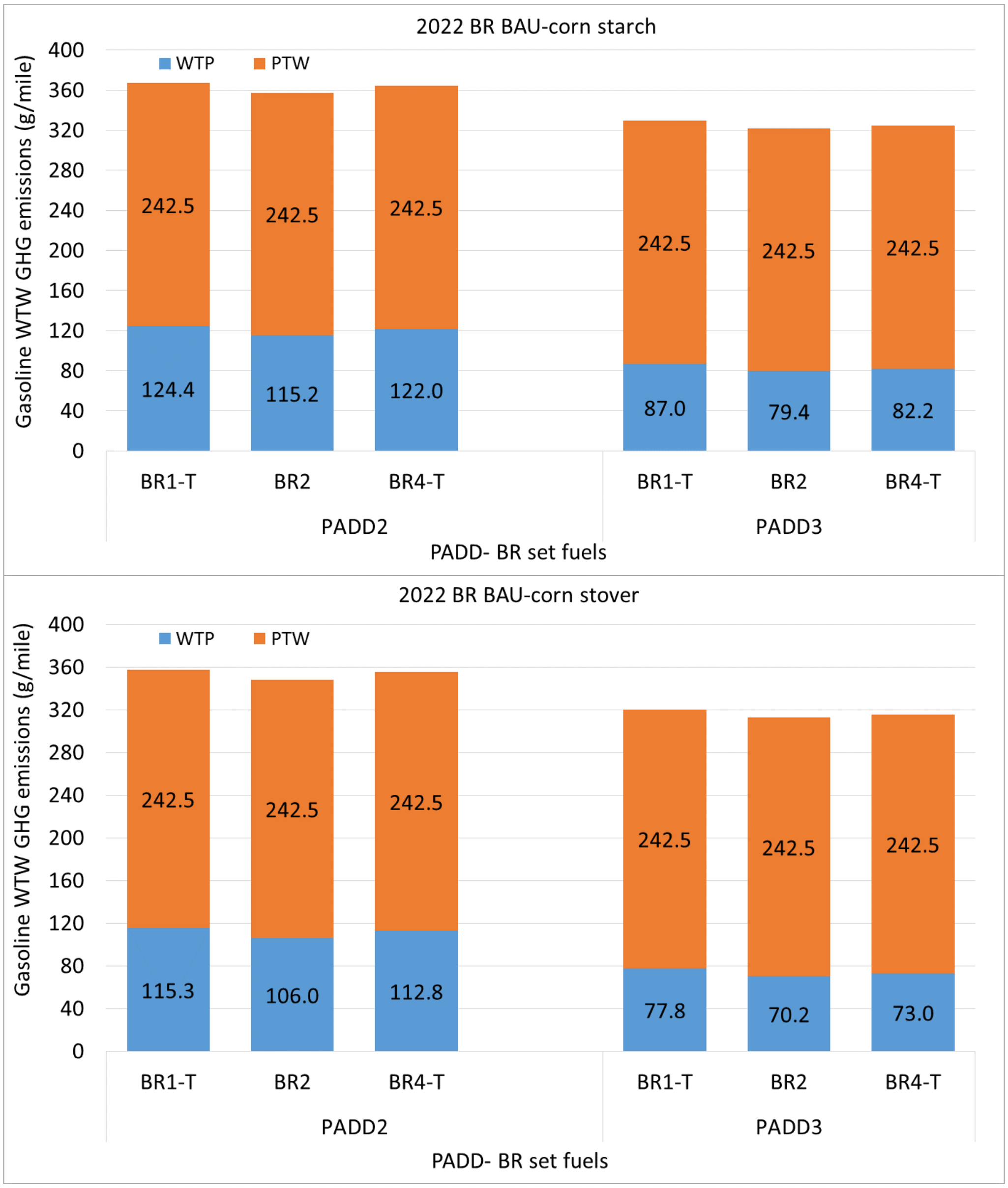


Figure 9-84. Per-Mile WTW GHG Emissions of BR BAU Gasolines with Two Ethanol Sources in 2022 (for ON/CR of 3.0)

Figure 9-85. Per-Mile WTW GHG Emissions of BR HOF Gasolines with Different Hydrogen Sources for BR production in 2022 (for ON/CR of 3.0)

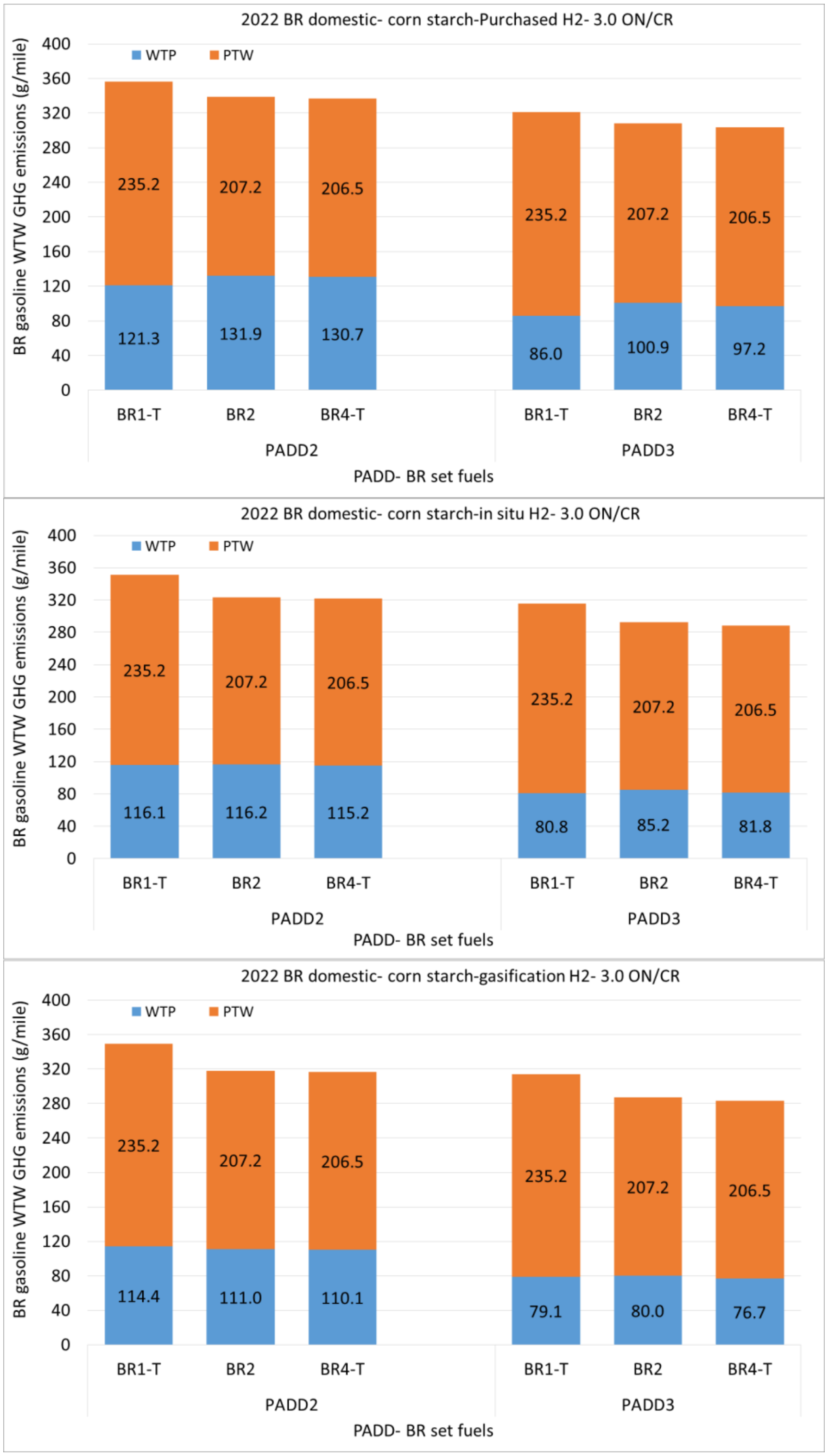


Figure 9-86. Per-Mile WTW GHG Emissions of BR Domestic Gasolines with Corn Starch Ethanol in BAU Gasoline and Different Hydrogen Sources for BR Production in 2022 (for ON/CR of 3.0)

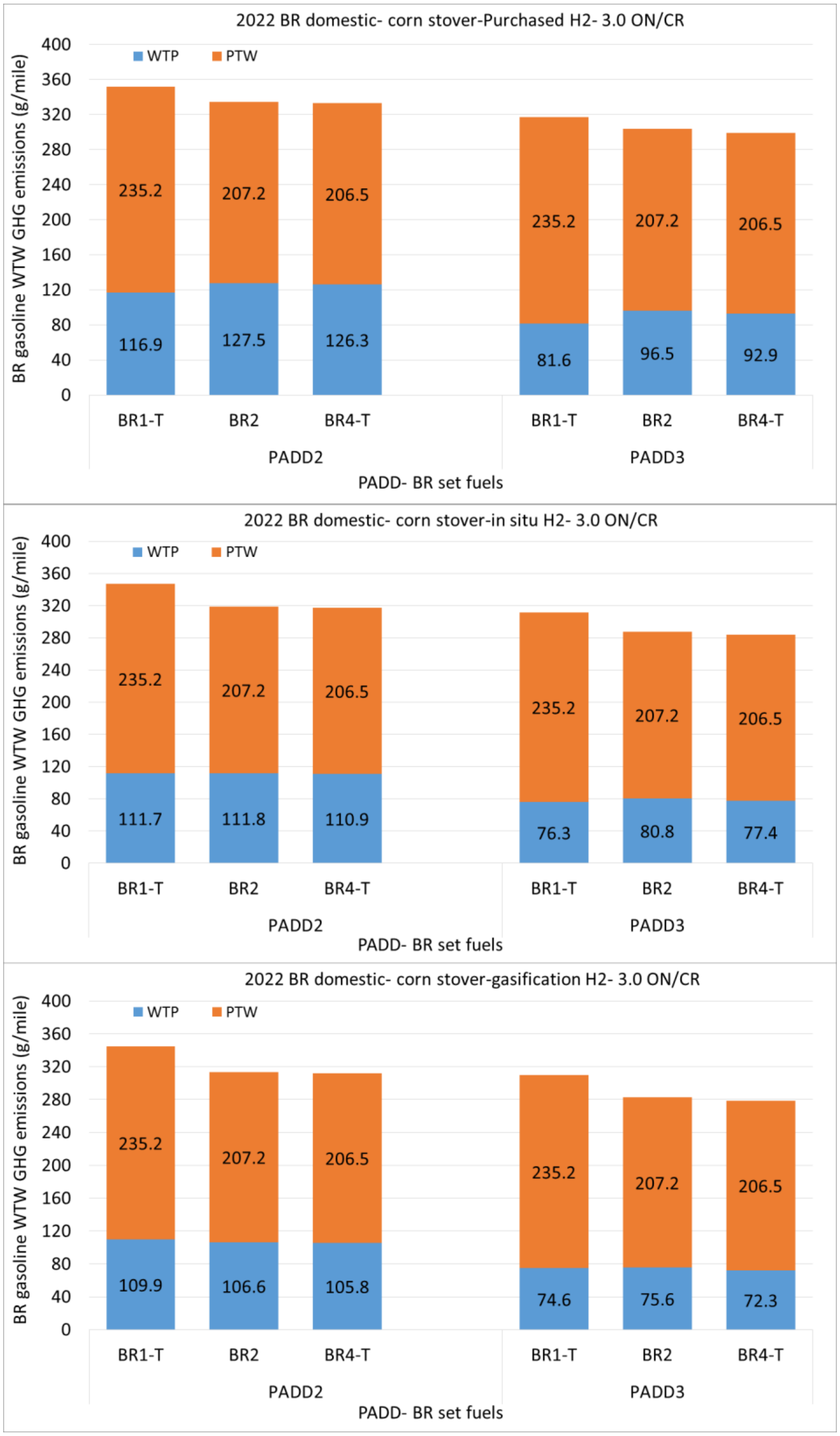


Figure 9-87. WTW GHG Emissions of BR Domestic Gasolines with Corn Stover Ethanol in BAU Gasoline and Different Hydrogen Sources for BR Production in 2022 (for ON/CR of 3.0)

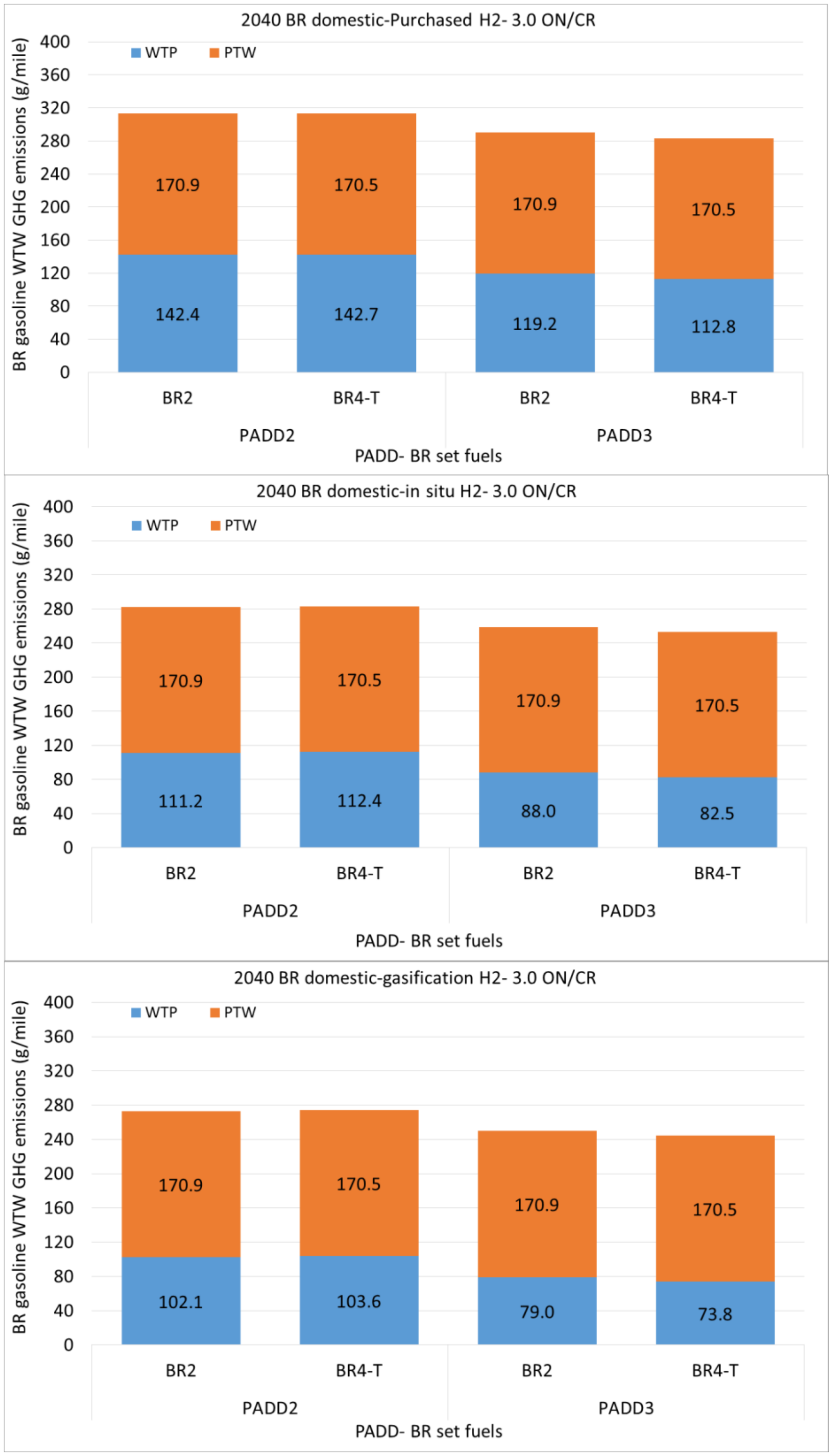


Figure 9-88. Per-Mile WTW GHG Emissions of BR Domestic Gasolines with Different Hydrogen Sources for BR Production in 2040 (for ON/CR of 3.0)

The GHG emissions of BR domestic gasolines in aggregate refineries with fuel economies under ON/CR of 3.7 and 5.6 show similar trends, and their values are shown in Table 9-14.

Table 9-14. BR Domestic Gasoline Pool Per-Mile WTW GHG Emissions in 2022, with Ethanol in BAU Gasoline from Corn Starch or Corn Stover, and Bioreformate Produced from Different Hydrogen Sources

Fuel	Corn Starch (g/mile)			Corn Stover (g/mile)		
ON/CR	3 ON/CR	3.7 ON/CR	5.6 ON/CR	3 ON/CR	3.7 ON/CR	5.6 ON/CR
Purchased H_2						
PADD2-BR1-T	356.5	357.7	359.4	352.1	353.3	354.9
PADD2-BR2	339.1	340.2	341.8	334.6	335.4	337.3
PADD2-BR4-T	337.1	338.3	340.5	332.8	333.9	336.1
PADD3-BR1	321.2	322.3	323.8	316.7	317.8	319.3
PADD3-BR2	308.0	309.1	310.5	303.6	304.1	306.0
PADD3-BR4-T	303.7	304.8	306.7	299.3	300.2	302.3
In-situ H_2						
PADD2-BR1-T	351.2	352.4	354.1	346.8	348.0	349.7
PADD2-BR2	323.3	324.4	325.9	318.9	320.0	321.5
PADD2-BR4-T	321.7	322.8	324.8	317.3	318.4	320.4
PADD3-BR1	315.9	317.0	318.5	311.5	312.6	314.1
PADD3-BR2	292.3	293.3	294.7	287.9	288.9	290.2
PD3-BR4-T	288.2	289.3	291.1	283.9	284.9	286.7
Gasification H_2						
PADD2-BR1-T	349.5	350.7	352.4	345.1	346.3	347.9
PADD2-BR2	318.2	319.3	320.7	313.8	314.8	316.3
PADD2-BR4-T	316.6	317.7	319.7	312.2	313.3	315.3
PADD3-BR1	314.2	315.3	316.8	309.8	310.9	312.3
PADD3-BR2	287.2	288.1	289.5	282.7	283.7	285.0
PADD3-BR4-T	283.2	284.2	285.9	278.8	279.8	281.5

Along the WTW life cycle, changes in fuel economy under different ON/CR assumptions have only a small impact on the GHG emissions of BR set fuels in 2022, about 1-3 g/mile. In contrast, different hydrogen sources have large impact on the GHG emissions, about 5-21 g/mile, with largest benefits for gasification hydrogen production. As expected, BR set fuels have the highest GHG emissions when hydrogen is purchased, and lower GHG emissions when hydrogen is provided via biomass in-situ production or biomass gasification.

Table 9-15. BR Set Fuel Per-Mile WTW GHG Emissions in 2040, with BR Stream from Different Hydrogen Sources

PADD- BR Set Fuel	GHG Emissions (g/mile)		
ON/CR	3 ON/CR	3.7 ON/CR	5.6 ON/CR
Purchased H_2			
PD2-BR2	313.2	315.3	318.1
PD2-BR4-T	313.2	315.3	319.1
PD3-BR2	290.1	292.0	294.6
PD3-BR4-T	283.3	285.3	288.7
In-situ H_2			
PD2-BR2	282.0	283.8	286.4
PD2-BR4-T	282.9	284.8	288.3
PD3-BR2	258.9	260.6	262.9
PD3-BR4-T	253.1	254.8	257.8
Gasification H_2			
PD2-BR2	273.0	274.8	277.2
PD2-BR4-T	274.2	276.0	279.4
PD3-BR2	249.9	251.5	253.7
PD3-BR4-T	244.3	246.0	248.9

In 2040, the differences in WTW GHG emissions among BR set fuels with different hydrogen sources are about 10-40 g/mile, with 100% HOF share in domestic gasoline. A comparison of BR set fuels GHG emissions to baselines on a per-mile basis is shown in Figure 9-89.

BR set fuels with purchased hydrogen have the highest GHG emissions, showing the least GHG reduction benefits compared with baselines (the continuing use of BAU fuels). Reductions range from 0.4% to 8%. In-situ hydrogen production to produce bioreformate gives a greater reduction in GHG emissions, with the reduction reaching 1% to 12%. The BR set fuels produced with gasification hydrogen show the greatest GHG reductions, ranging from 1% to 14%.

Overall, corn starch ethanol cases (in BAU gasolines) show smaller GHG emission reductions both compared with baselines and compared to corn stover ethanol cases (both compared with E10 baselines with ethanol from corn starch). Again, in 2040, the BR fuels with various hydrogen sources are compared with dual baselines with corn starch ethanol or corn stover ethanol. See Figure 9-90.

In 2040, only the high-blending BR fuels (BR2 and BR4-T set fuels) have feasible solutions without refinery investment. The cases relative to baseline E10 with corn starch ethanol show greater GHG emission reductions than those with corn stover ethanol.

All three BR hydrogen sources result in WTW GHG emissions reductions compared with baselines, leading to sizeable reductions of 15% to 21% with in-situ hydrogen, and 19% to 24% reductions with gasification hydrogen. Even with purchased hydrogen, the BR set fuel WTW GHG emissions are about 6%–12% lower than baselines.

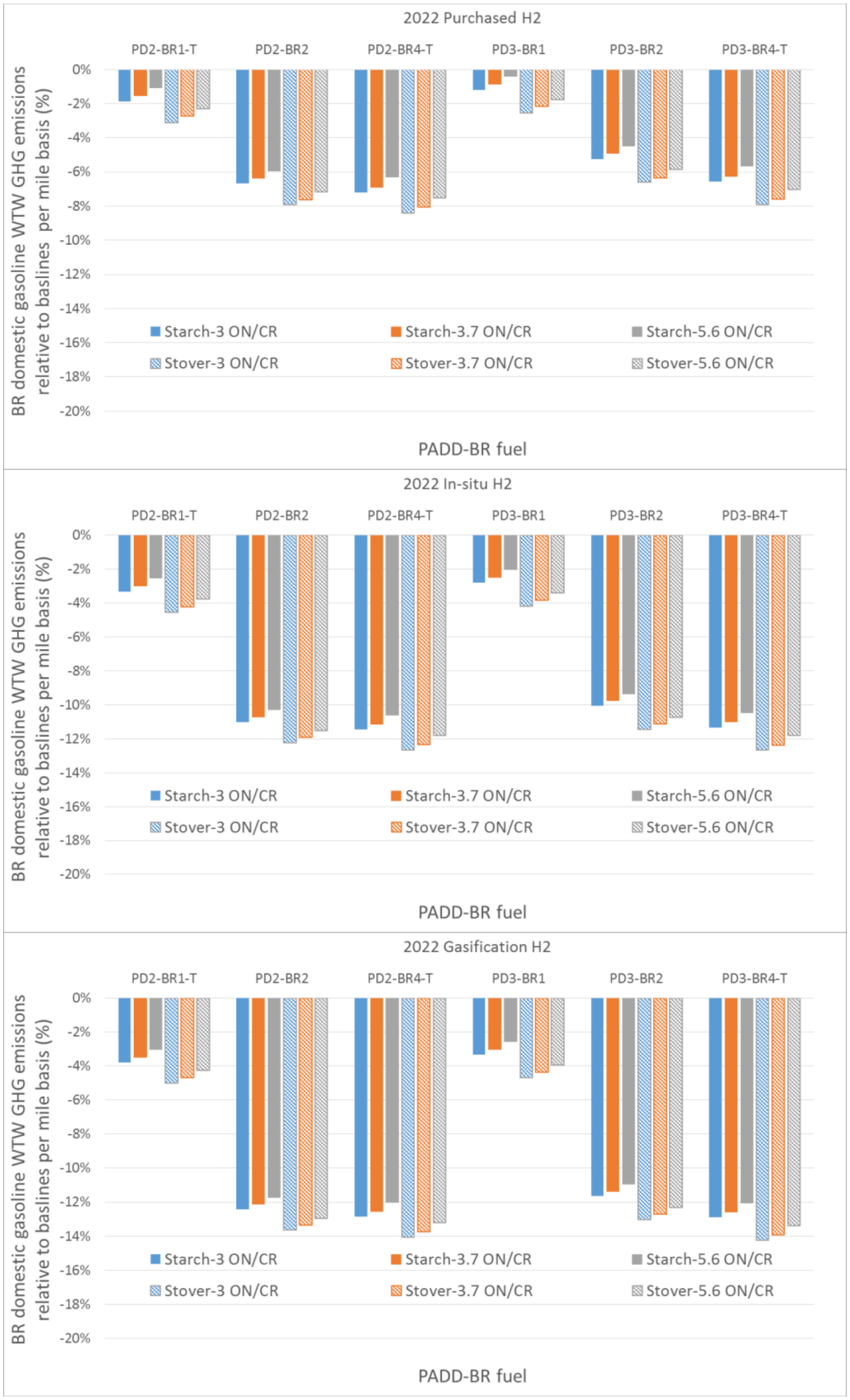


Figure 9-89. Per-Mile Changes of WTW GHG Emissions of BR Domestic Gasolines Relative to Baselines in 2022 with Different Ethanol Sources in BAU Gasoline and Bioreformate Produced from Different Hydrogen Sources. Baselines Uses Corn Starch Ethanol

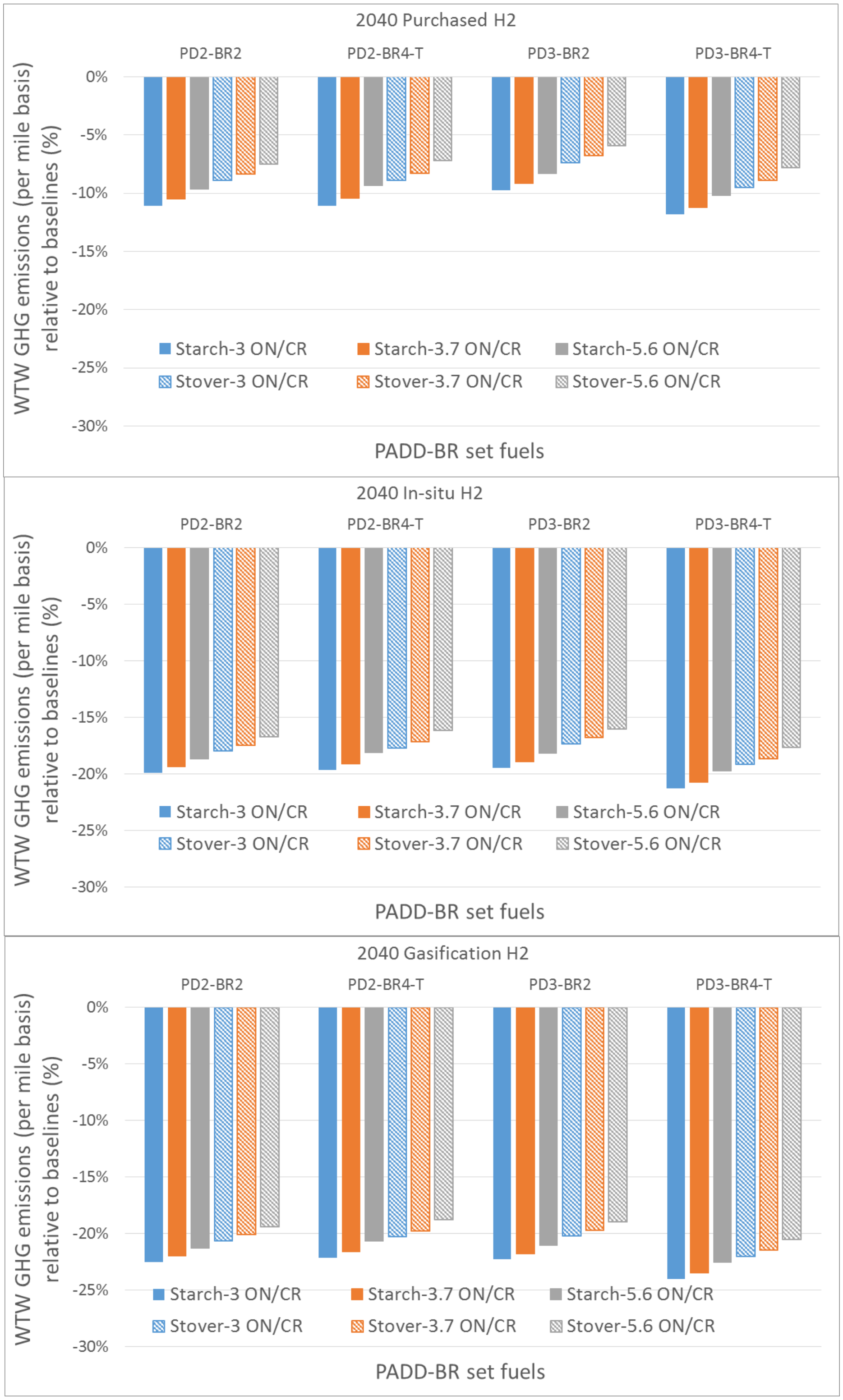


Figure 9-90. Per-Mile WTW GHG Emissions of BR Set Fuels in 2040 with Different Hydrogen Sources for Bioreformate Production. Dual Baselines Used with Corn Starch Ethanol or Corn Stover Ethanol

9.2.2 WTW Results of BR Set Fuels Production with Configuration Refineries

9.2.2.1 WTW Energy Use of BR Fuels from Configuration Refineries

The energy use of BR set fuels produced in configuration refineries varies in multiple dimensions: the refinery configuration used for gasoline BOB production, the hydrogen source for BR production, and the corn source for ethanol production. The different RONs of the BR fuels introduce yet another dimension.

WTW energy use of BR set BAU and HOF gasolines in 2022 are summarized in Figure 9-91 and Figure 9-92, broken down into WTP and PTW stages, with the former varying with ethanol source and the latter varying with hydrogen source. In 2040, the BR domestic gasolines do not contain ethanol, thus their WTW energy use vary only with hydrogen source for bioreformate production. There is no data for the COKHCK configuration nor for BR1 and BR3 fuels because all of those cases were “infeasible” in the refinery modeling.

As expected, the BR fuel WTP energy use increases with increasing refinery complexity. Of the BR BAU gasolines produced in configuration refineries, BR2 uses slightly less energy than BR4-T gasoline for a given refinery configuration. The BAU gasoline with corn starch ethanol uses less total energy but slightly more fossil energy than with corn stover ethanol, and its use of petroleum energy is similar. The difference is small, as only 10% ethanol is blended into the BAU gasoline.

As shown in Figure 9-92, for HOF gasoline in 2022, the energy use difference between BR 2 and BR4-T is slightly more pronounced (0.02–0.03 MJ/MJ or about 1%), as 27% bioreformate is blended, and unlike the BAU gasoline results, BR2 HOF has higher energy use than BR4-T. The detailed energy uses were given in Section 6 in terms of gasoline production energy intensity.

WTW energy use for the BR domestic gasolines produced in the configuration refineries is shown in Figures 9-93, 9-94 and 9-95.

Fossil energy use for the BR domestic finished gasolines increases with increasing refinery complexity. With higher energy use for BAU, but lower energy use for HOF, the combined domestic gasoline of BR4 has similar energy use to BR2.

The WTW energy use of these BR set fuels in 2022 and 2040 are also discussed from another perspective, shown in terms of petroleum, NGC and renewable energy use in Figures 9-96 and 9-97 with ethanol from corn starch and corn stover, respectively. In 2040, the energy uses only vary with hydrogen sources.

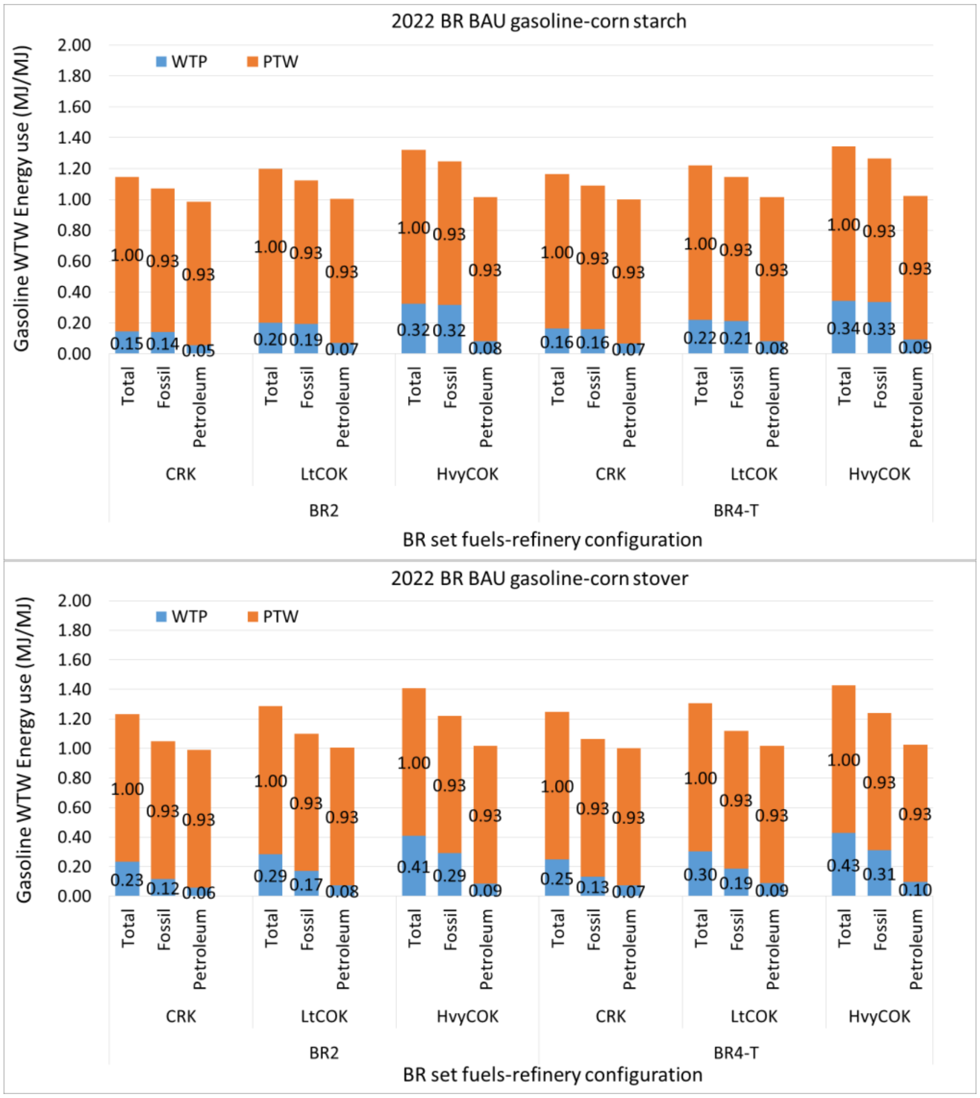


Figure 9-91. WTW Energy Uses of BR BAU Finished Gasolines Produced in Configuration Refineries in 2022 (MJ/MJ of Fuel)

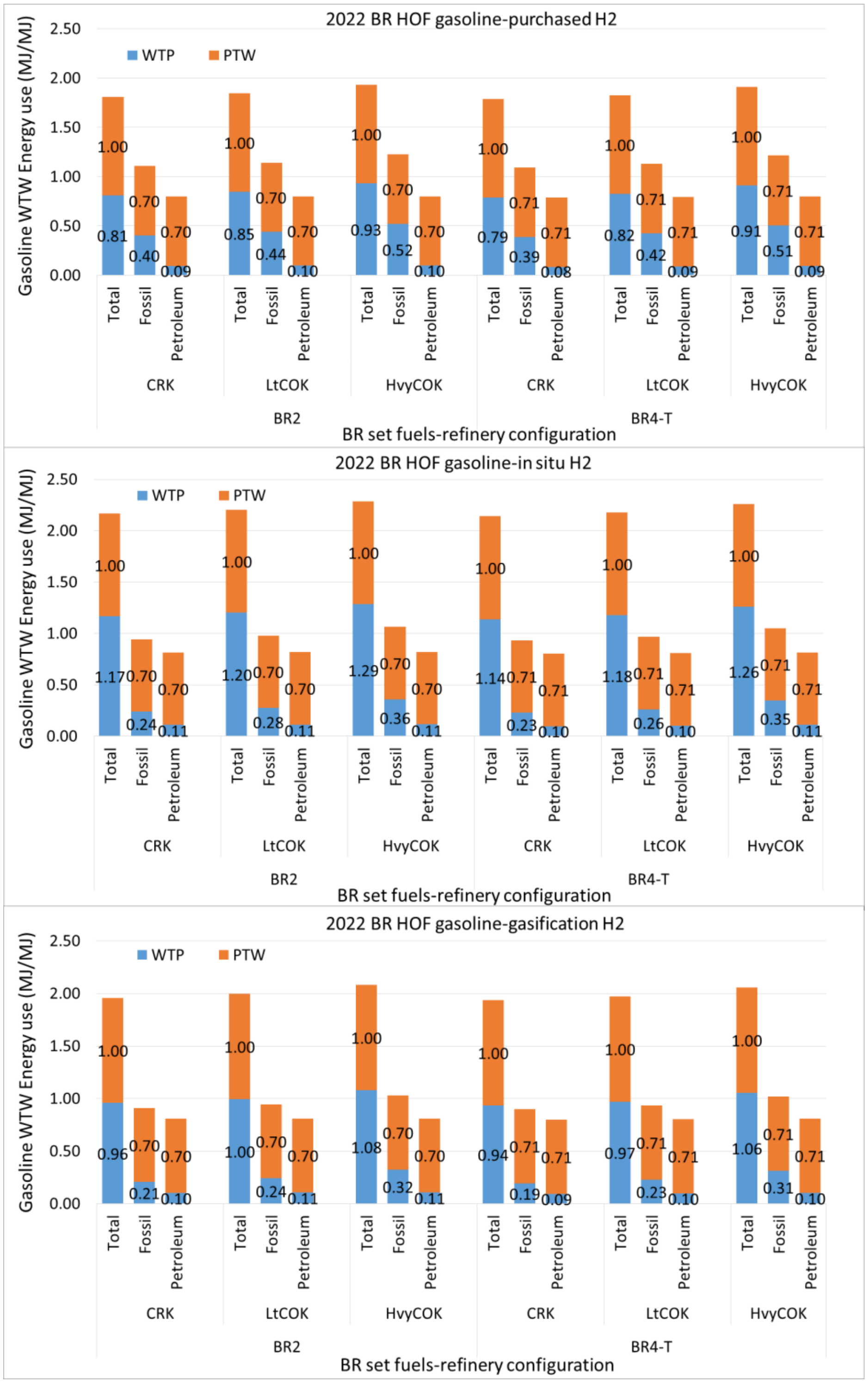


Figure 9-92. WTW Energy Uses of BR HOF Gasoline Produced in Configuration Refineries in 2022 (MJ/MJ of Fuel)

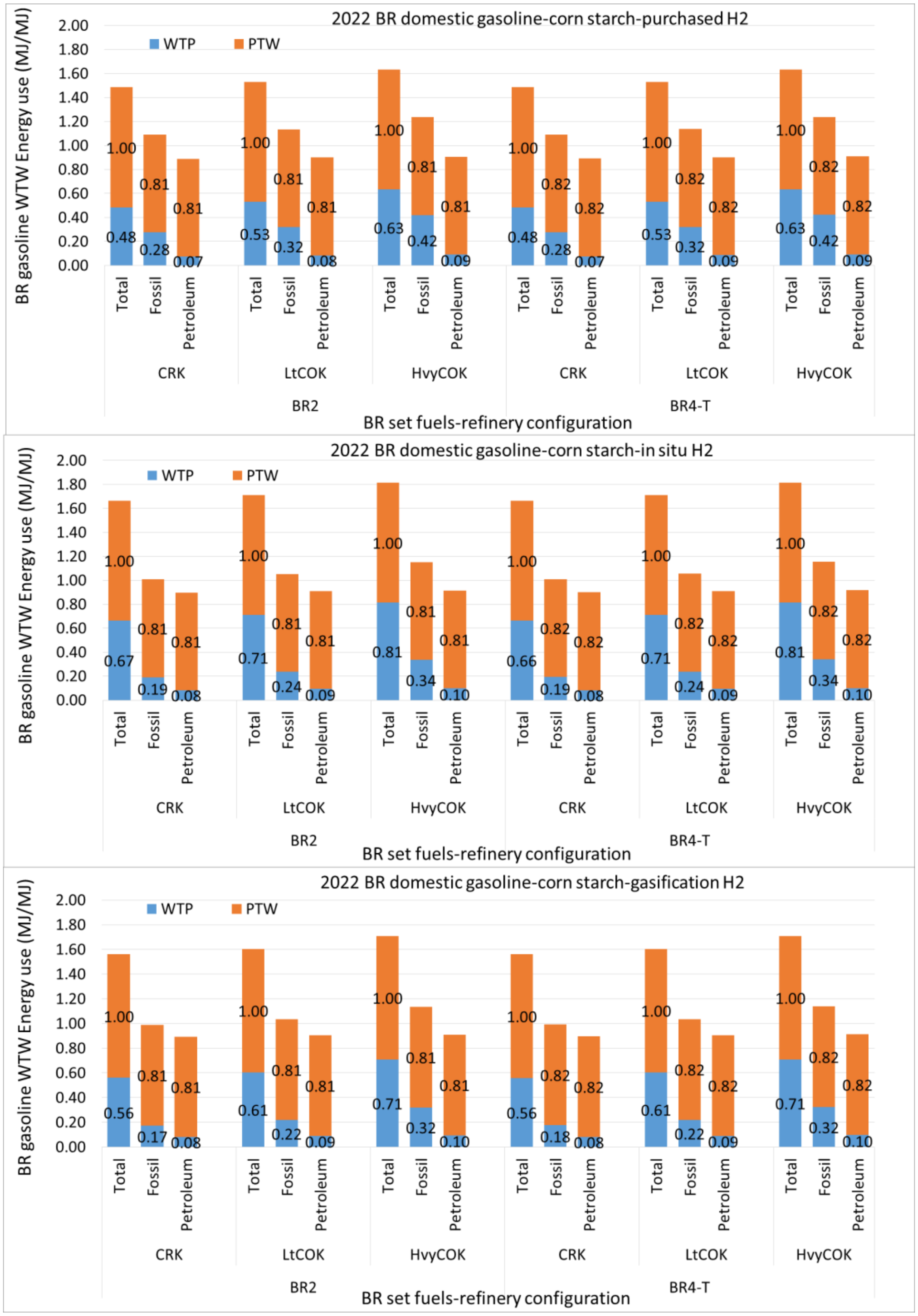


Figure 9-93. WTW Energy Uses of BR Domestic Finished Gasolines Produced in Configuration Refineries with Ethanol from Corn Starch and Bioreformate Using Different Hydrogen Sources in 2022

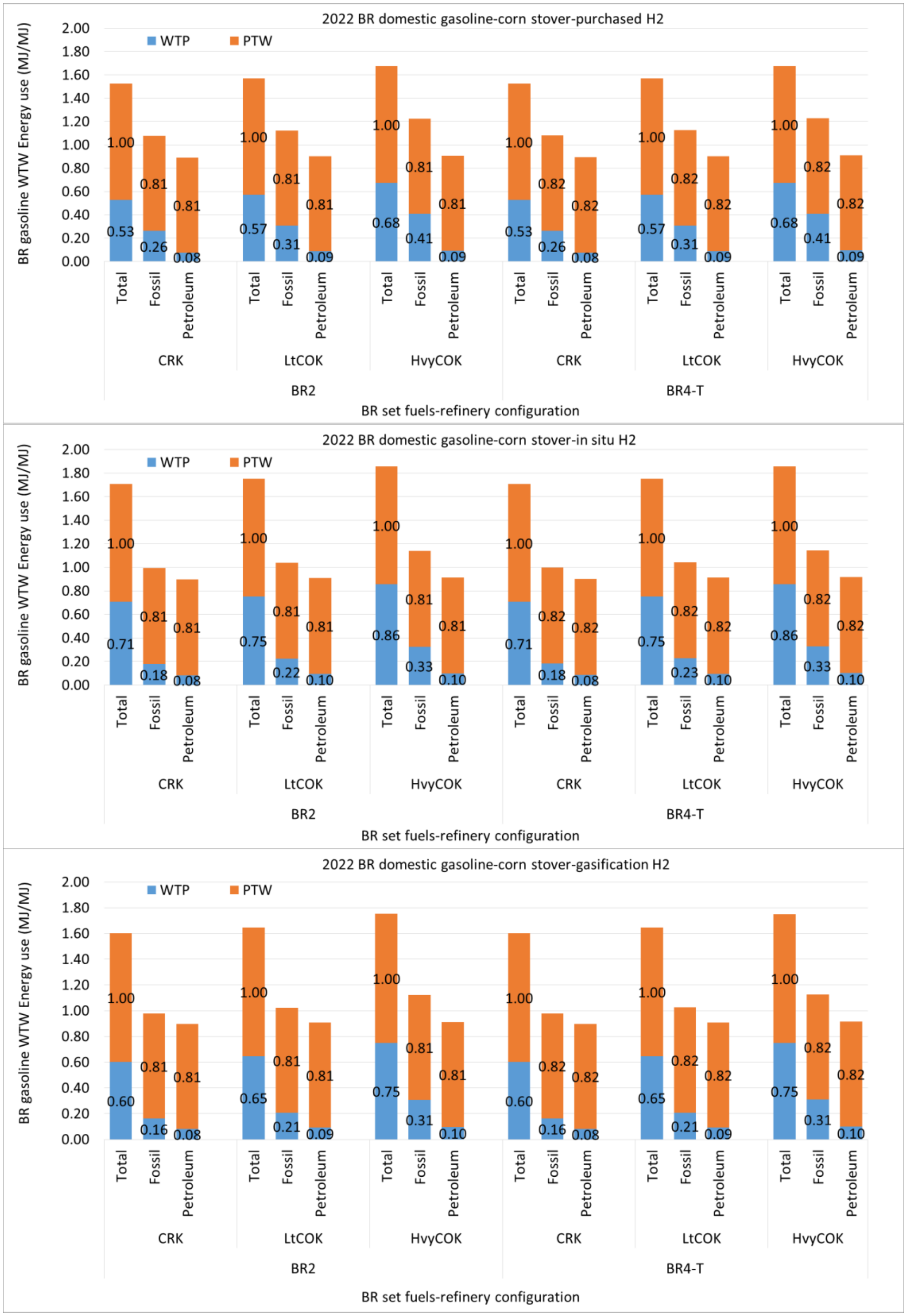


Figure 9-94. WTW Energy Uses of BR Domestic Gasolines Produced in Configuration Refineries with Ethanol from Corn Stover and Bioreformate Using Different Hydrogen Sources in 2022

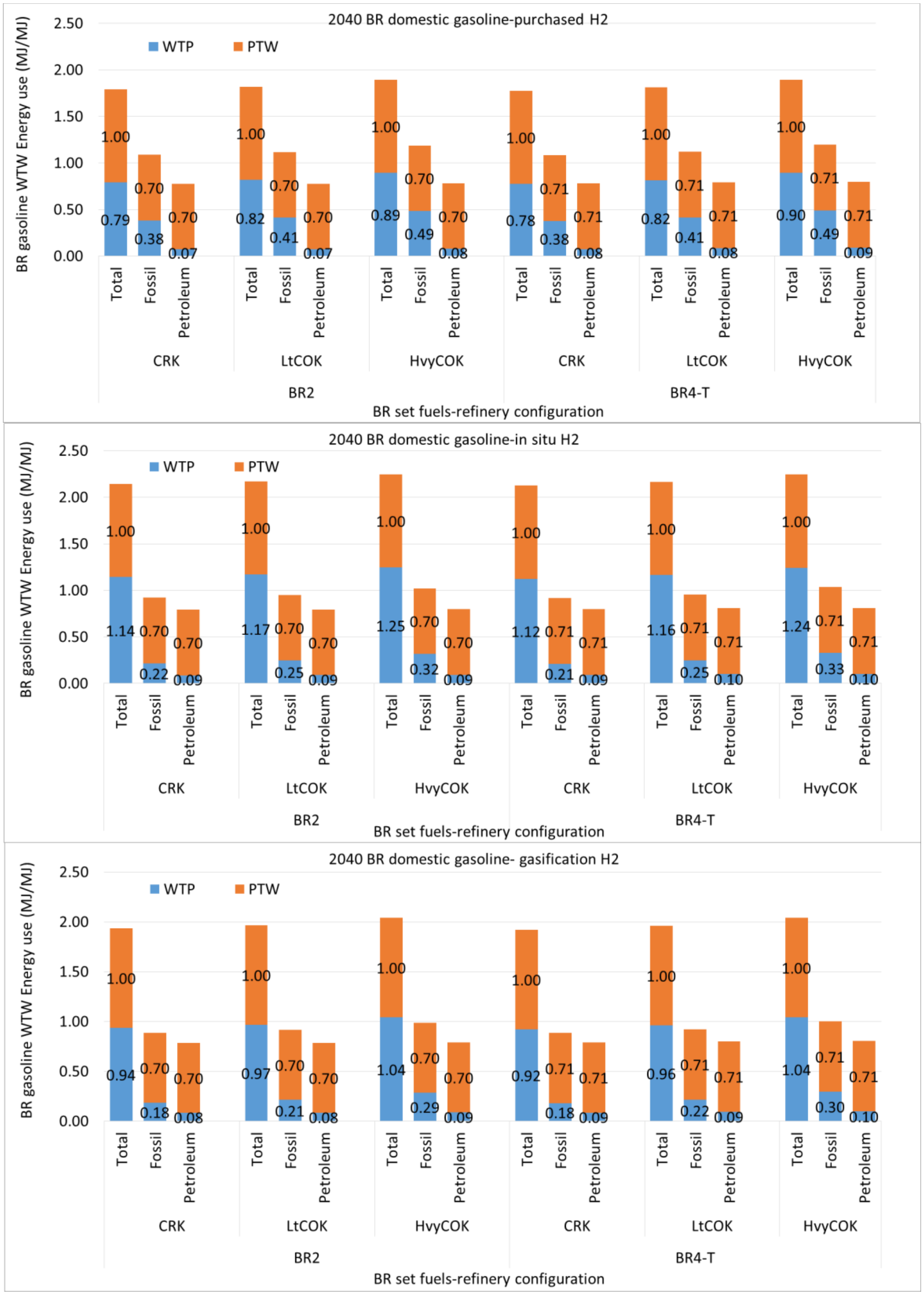


Figure 9-95. WTW Energy Uses of BR Domestic Finished Gasolines Produced in Configuration Refineries with Bioreformate Produced Using Different Hydrogen Sources in 2040

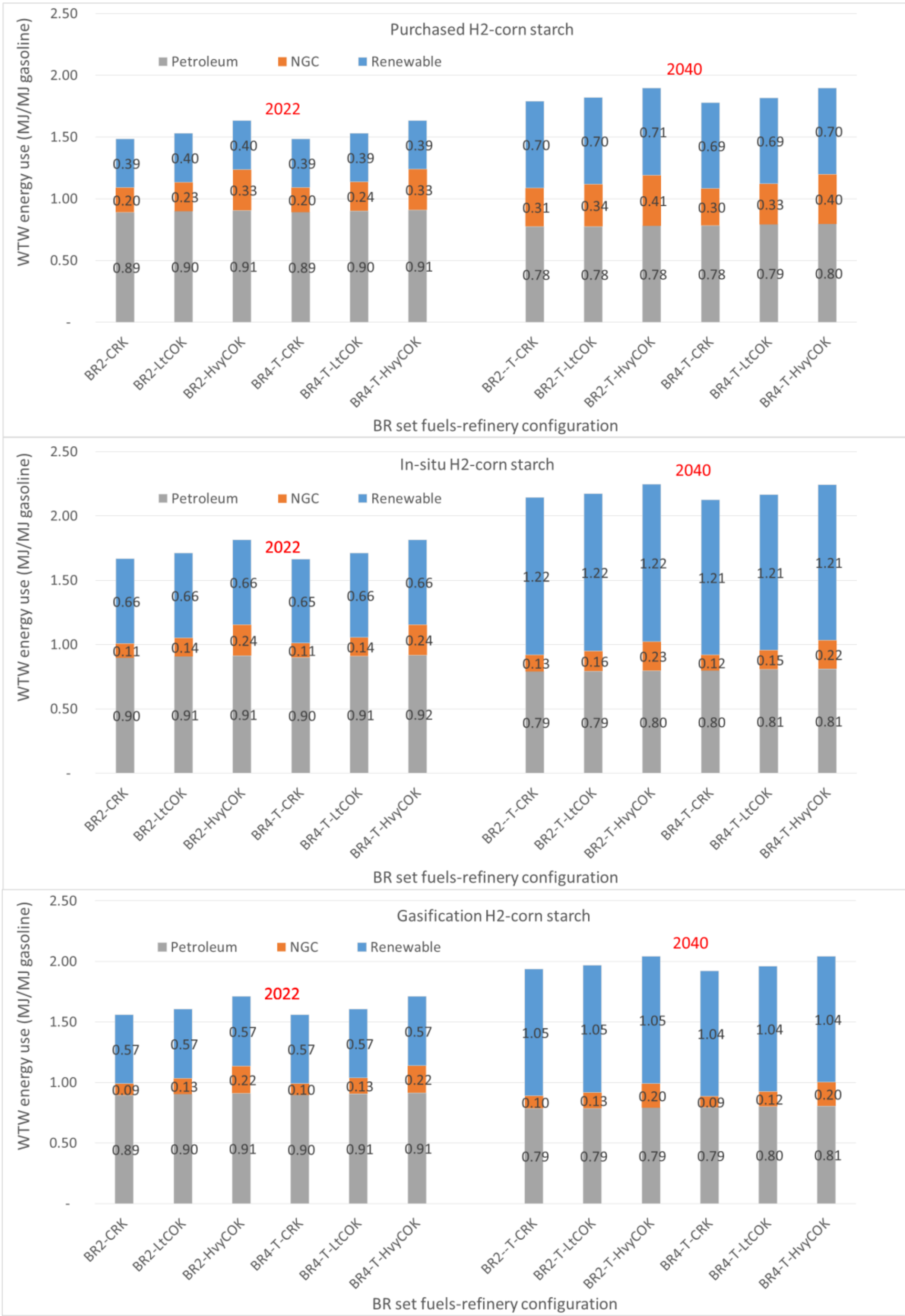


Figure 9-96. WTW Energy Uses of BR Set Fuels Produced in Configuration Refineries in 2022 and 2040 (MJ/MJ of Fuel) with Bioreformate Produced with Different Hydrogen Sources. In 2022 BAU Gasoline Has Ethanol from Corn Stover

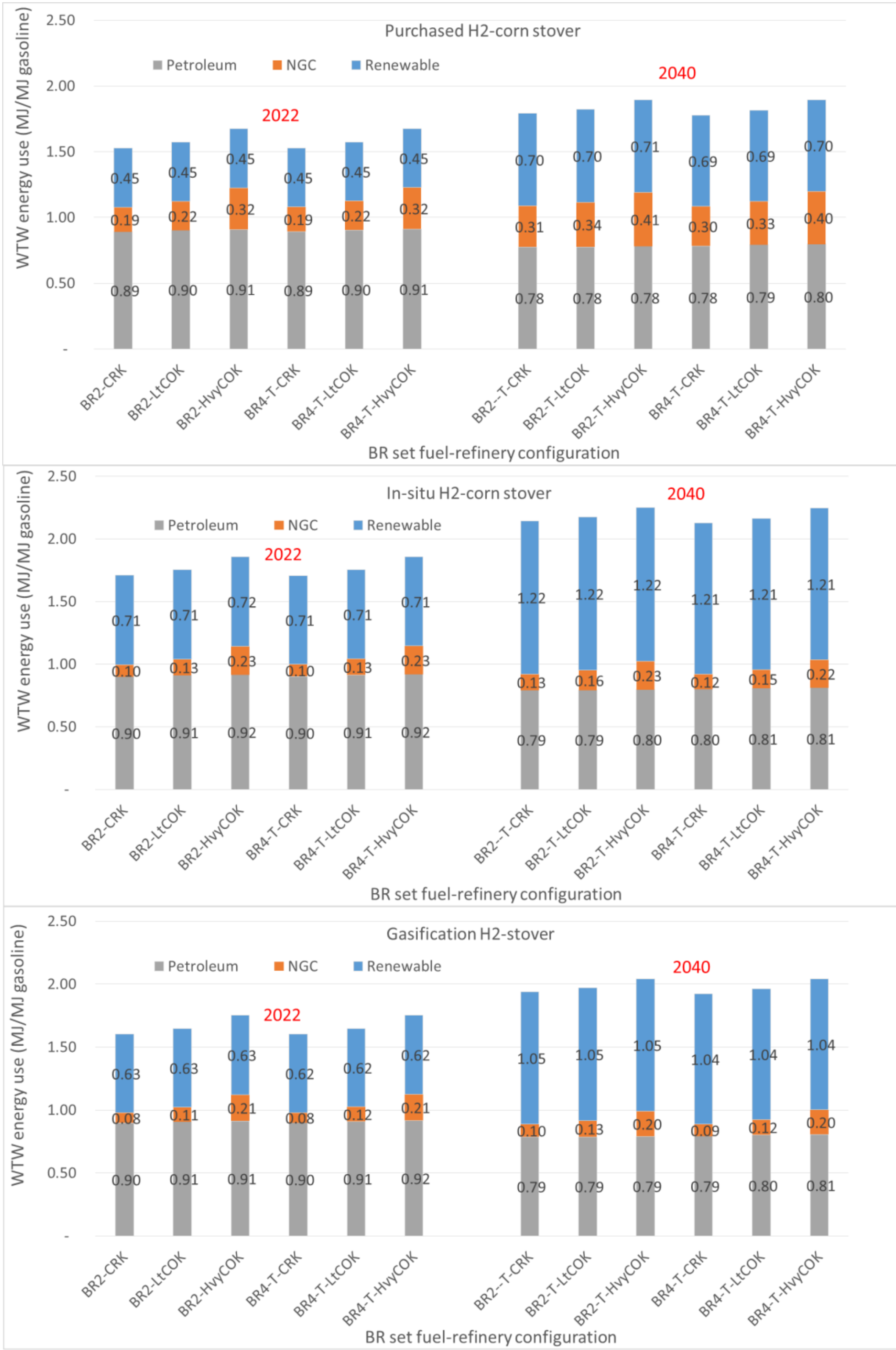


Figure 9-97. Energy Use of BR Set Fuels Produced in Configuration Refineries in 2022 and 2040 (MJ/MJ of Fuel) with Bioreformate Produced with Different Hydrogen Sources. In 2022 BAU Gasoline Has Ethanol from Corn Stover

The impact of each aspect for the 2022 and 2040 results is briefly described below.

Configuration: A comparison of the energy use for BR set fuel production in different refinery configurations shows that for each BR set fuel, the fuel produced in a HvyCOK refinery has the highest energy use, mostly due to differences in NGC use, and the rest, as discussed earlier, due to crude slate, refinery operation, refinery hydrogen demand, and other factors. The impact of refinery configuration is a difference of about 0.05–0.15 MJ/MJ (about 5%–10%) for total energy use, 0.03–0.1 MJ/MJ for fossil energy use (about 5%–10%), and 0.01–0.02 MJ/MJ (about 1%–2%) for petroleum energy use. The different refinery configurations have a noticeable impact on the BR set fuels' WTW energy use for both years.

Ethanol source: The impact of ethanol source is a difference of about 0.03–0.05 MJ/MJ for total energy use, 0.04–0.05 MJ/MJ for renewable energy, 0.01–0.02 MJ/MJ for natural gas+coal energy, and negligible changes for petroleum energy. So different ethanol sources have a very small impact on BR set fuel WTW energy use in 2022. In 2040, the BR set fuels do not contain ethanol.

RON: BR4/BR4-T (101 RON) fuels have slightly higher energy use than BR2/BR2-T (97 RON) fuels. The impact of RON is a difference of about 0.01–0.02 MJ/MJ for petroleum energy use. RON has a small or negligible impact on BR set fuel WTW energy use in 2022 and in 2040.

Hydrogen source: The hydrogen source has a sizeable impact on the BR set fuels WTW energy uses. In 2022, the impact of the hydrogen source is a difference of about 0.11–0.22 MJ/MJ difference for total energy use, 0.01–0.12 MJ/MJ for natural gas/coal energy use, and 0.01–0.02 MJ/MJ for petroleum energy use. In 2040, the hydrogen source impact increases to 0.21–0.35 MJ/MJ for total energy use, 0.03–0.21 MJ/MJ for natural gas/coal energy use, and 0.01–0.02 MJ/MJ for petroleum energy use.

Consistent with the trends observed for BR set fuels produced in PADD refineries, BR fuels with purchased hydrogen have the lowest total energy use and lowest petroleum energy use (although the difference is very small, about 0.01 MJ/MJ), but the highest fossil energy use (mostly because of differences in natural gas/coal use). In contrast, BR fuels with gasification hydrogen have the lowest fossil energy use, and the BR fuels with in-situ hydrogen have the highest total energy use.

In 2040, with 100% HOF production, the WTW renewable energy use of each BR set fuel with renewable hydrogen (in-situ hydrogen and gasification hydrogen) is significant — more than fossil energy use.

BR energy use for 2022 and 2040 compared with baselines using ethanol from corn starch and from corn stover is shown in Figures 9-98 and 9-99, respectively.

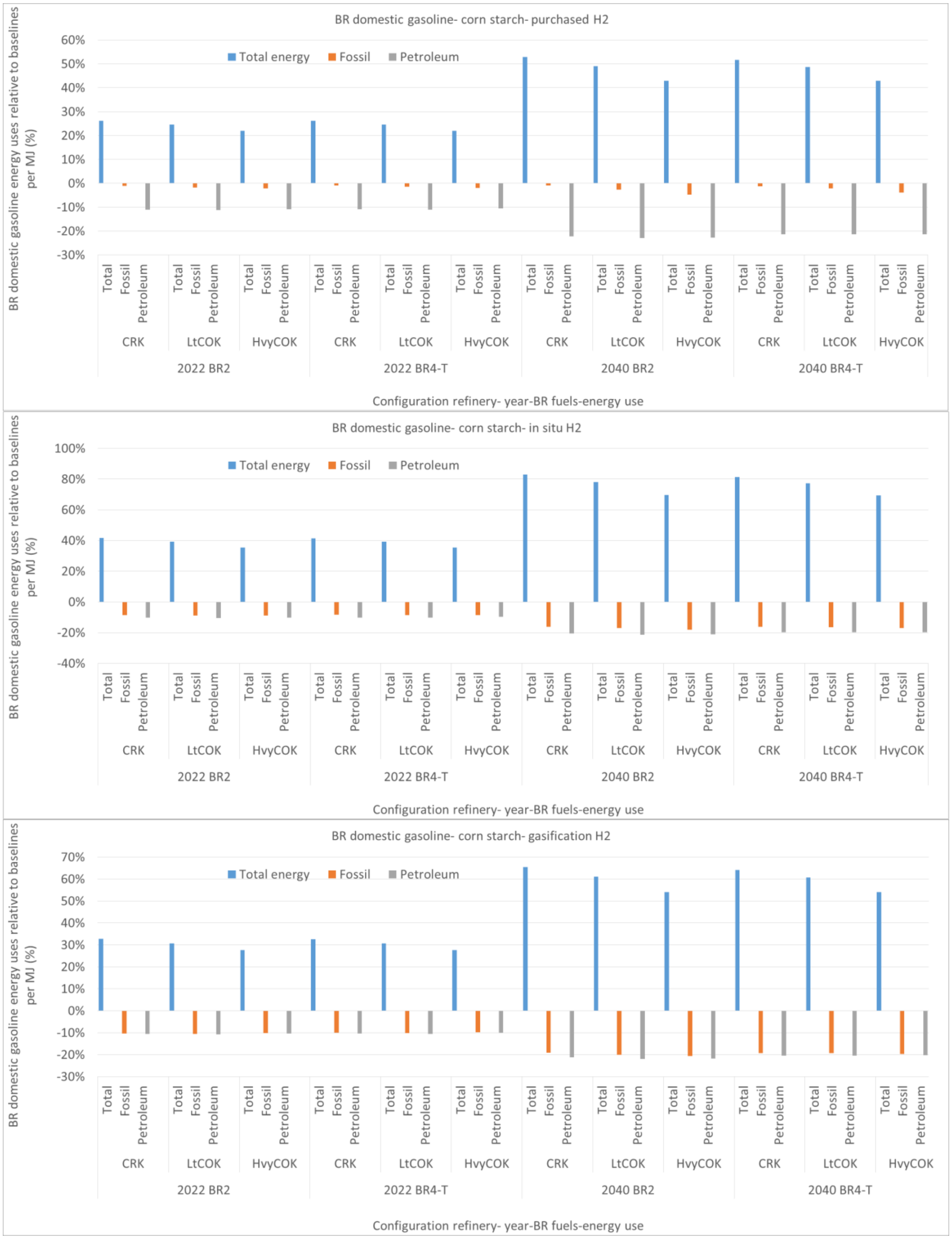


Figure 9-98. Per-MJ Changes in WTW Energy Uses of BR Domestic Finished Gasolines (Bioreformate Produced Using Three Hydrogen Sources) Relative to Baselines. In 2022, BAU Gasoline and Baselines Use Corn Starch Ethanol. In 2040, BR Domestic Gasoline Has No Ethanol and Baselines Use Corn Starch Ethanol

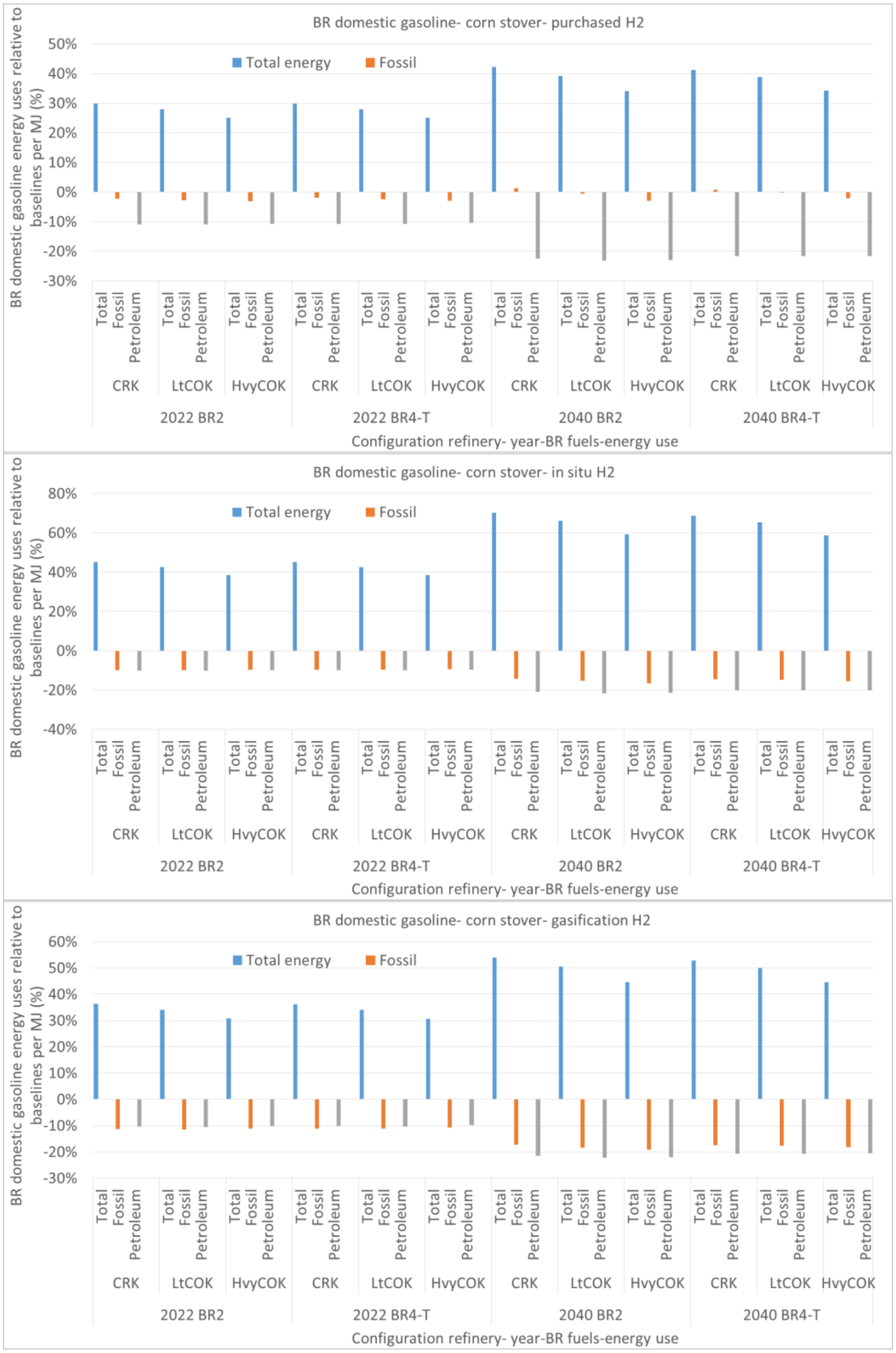


Figure 9-99. Per-MJ Changes in WTW Energy Uses of BR Domestic Finished Gasolines (Bioreformate Produced Using Three Hydrogen Sources) Relative to Baselines. In 2022, BAU Gasolines Use Corn Stover Ethanol and Baselines Use Corn Starch Ethanol. In 2040, BR Domestic Gasolines Have No Ethanol and Baselines Use Corn Stover Ethanol

Again, in 2022, BR fuels are compared with only one baseline—with corn starch ethanol. In 2040, BR fuels are compared with both corn starch ethanol and corn stover ethanol baselines.

In both 2022 and 2040, the fossil and petroleum energy use of BR domestic gasolines compared with baselines (which vary with configuration refinery) are similar for all three configuration refineries: total energy use variation from baseline decreases with increasing refinery configuration complexity. This is because the gasoline BOB energy use increases with increasing refinery configuration complexity, which leads to a decreased energy use share assigned to the bio-blend in the overall WTW range, the main source of variations from baselines. Overall, the reduction of fossil and petroleum energy use is larger in 2040 than in 2022.

Specific patterns observed for the BR gasolines include the followings:

BR domestic gasolines with purchased hydrogen: In 2022, a single baseline with corn starch ethanol is used. For BR domestic gasolines with corn starch ethanol (in BAU gasoline pool), the total energy use is higher than baselines by 22%–26%, while the fossil energy use is reduced by 1%–2%, and the petroleum energy use is reduced by 10%–11%. For BR domestic gasolines with corn stover ethanol (in BAU gasoline pool), the total energy use is higher than baselines by 25%–30%, while the fossil energy use is reduced by 2%–3%, and the petroleum energy use is reduced by 10%–11%

In 2040, dual baselines are used. Relative to the baseline with corn starch ethanol, the BR set domestic gasolines show 42%–52% higher total energy use. Meanwhile, the fossil energy use is reduced by 2%–5%, and the petroleum energy use is reduced by 20-21%. Relative to baseline with corn stover ethanol, the BR fuels total energy use is 35%–40% higher than baselines, fossil energy use shows marginal increases or decreases relative to baselines, and petroleum energy use shows 20%–23% reduction.

BR domestic gasolines with in-situ hydrogen: In 2022, for BR domestic gasolines relative to corn starch ethanol (in BAU gasoline pool), the total energy use is 35%–42% higher than baselines. However, fossil energy use is reduced by 8% and petroleum energy use by 10%–11%. For BR fuels relative to corn stover ethanol (in BAU gasoline pool), the total energy use is 39%–45% higher than baselines, and both fossil energy use and petroleum energy use are reduced by 10%–11%.

In 2040, dual baselines are used. Relative to the baseline with corn starch ethanol, the BR set domestic gasolines show 65-80% higher total energy use. Meanwhile, the fossil energy use is reduced by 16%–17%, and the petroleum energy use is reduced by 19%–21%. Relative to baseline with corn stover ethanol, the BR fuels total energy use is 60%–70% higher than baselines, the fossil energy use is reduced by 14%–16%, and the petroleum energy use shows 20%–22% reduction.

BR domestic gasolines with gasification hydrogen: In 2022, for BR set domestic gasolines with corn starch ethanol (in BAU gasoline pool), the total energy use is 28%–32% higher than baselines. Meanwhile, fossil energy use and petroleum energy use are both reduced by about 10%. For BR set domestic gasolines containing corn stover ethanol (in BAU gasoline pool), the total energy use is 30%–37% higher than baselines, the fossil energy use is reduced by 8%–9% and the petroleum energy use is reduced by 10%.

In 2040, dual baselines are used. Relative to the baseline with corn starch ethanol, the BR set domestic gasolines show 55%–65% higher total energy use. Meanwhile, the fossil energy use is reduced by 16%–18%, and the petroleum energy use is reduced by 20%–21%. Relative to baseline with corn stover ethanol, the BR fuels total energy use is 60%–70% higher than baselines, the fossil energy use is reduced by 17%–19%, and the petroleum energy use shows 20%–22% reduction.

9.2.2.2 Per-MJ WTW GHG Emissions of BR Fuels in Configuration Refineries

The exported gasoline burden is zero for all BR set fuels produced in configuration refineries, as the exported gasolines associated with BR fuels production have energy intensities similar to or lower than baselines.

WTW GHG emissions of BR set fuels were investigated for two different years and three refinery configurations. In 2022, the GHG emissions for BAU gasoline vary with ethanol source, and GHG emissions of HOF gasoline vary with hydrogen sources, as shown in Figures 9-100 and 9-101.

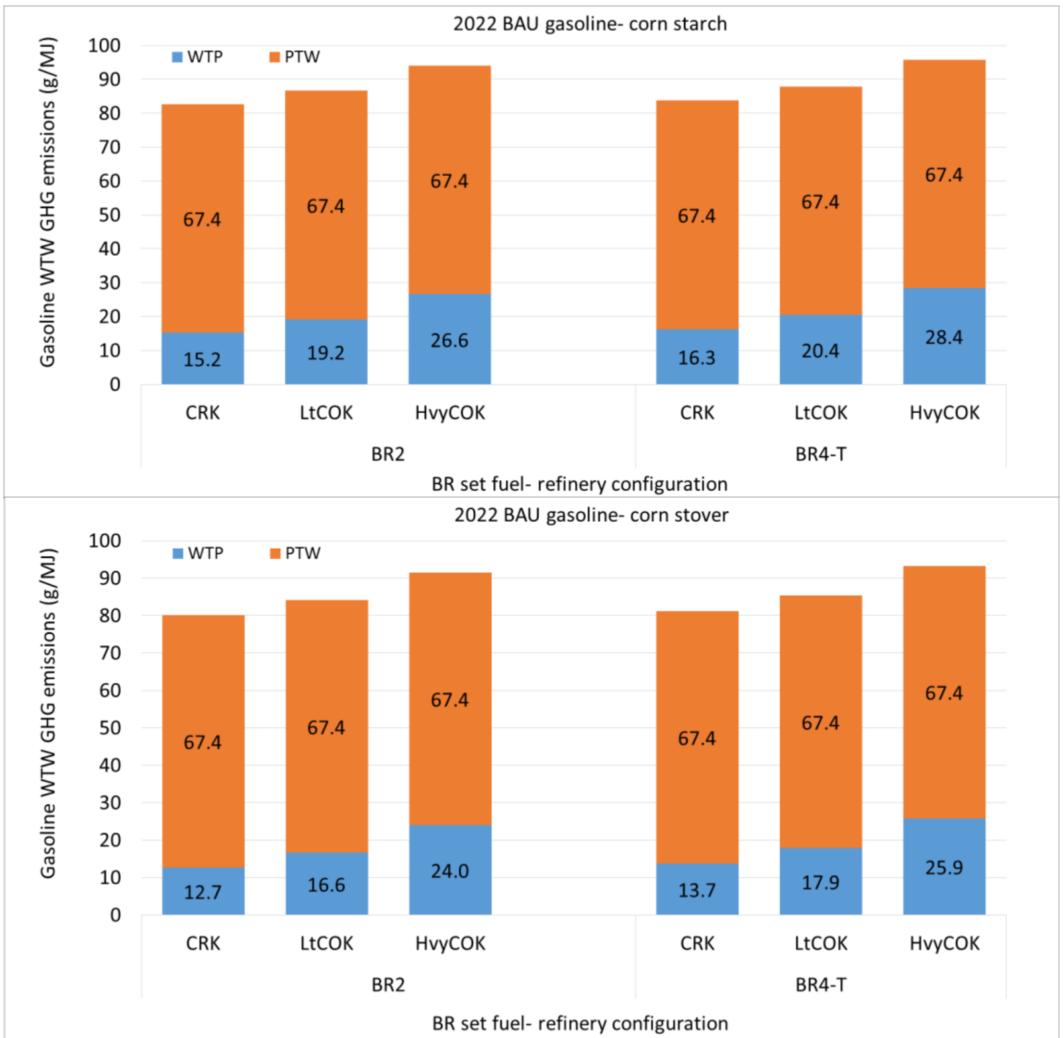


Figure 9-100. Per-MJ WTW GHG Emissions of BR BAU Gasoline in Configuration Refineries in 2022 with Corn Starch Ethanol and Corn Stover Ethanol

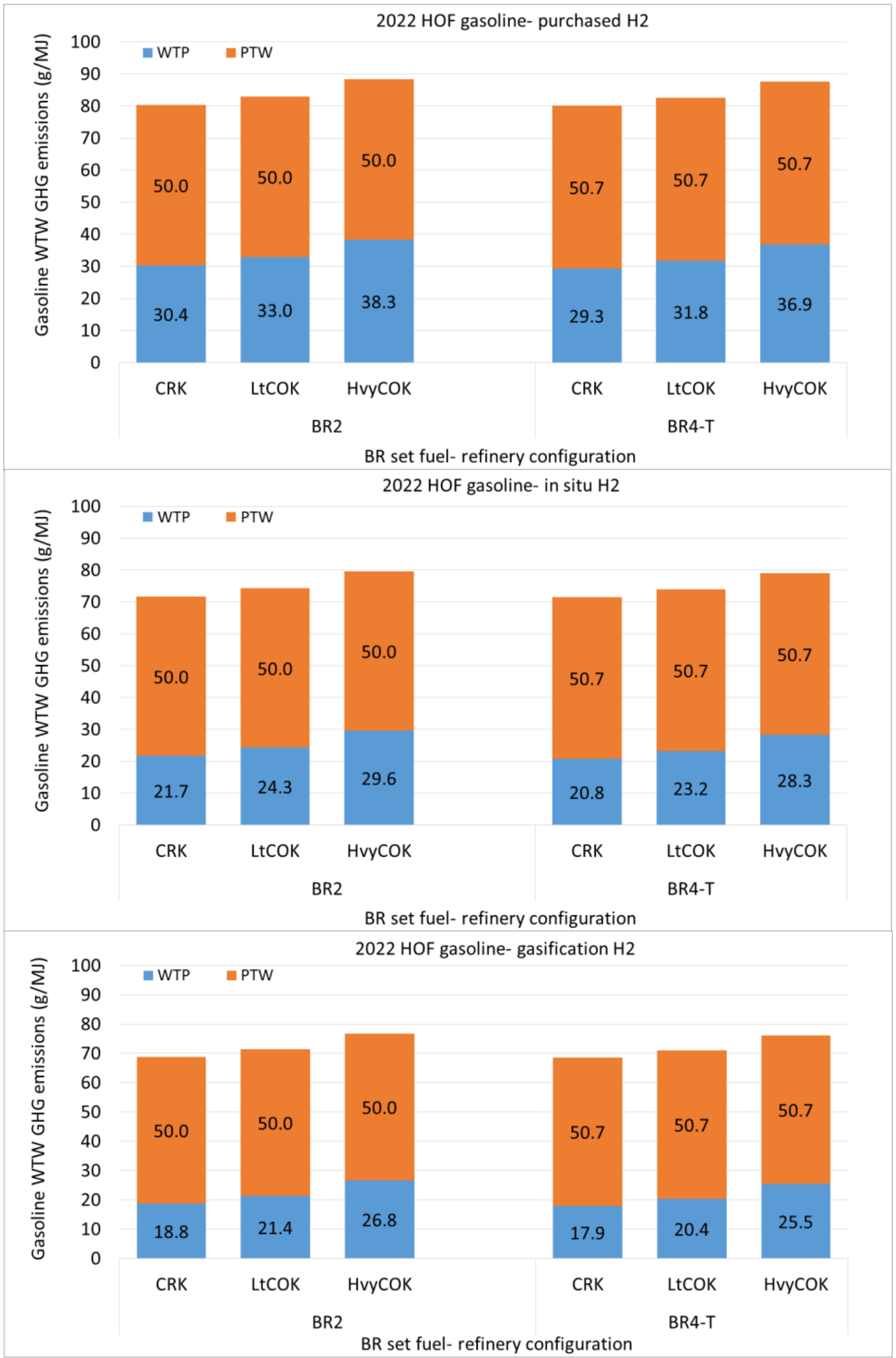


Figure 9-101. Per-MJ WTW GHG Emissions of BR HOF Gasoline in 2022 Produced in Configuration Refineries with Bioreformate Produced Using Different Hydrogen Sources

Consistent with the trends of fossil energy use, the WTW GHG emissions of BR set domestic gasoline have the following trends:

1. GHGs increase with refinery complexity in the order of CRK <LTCOK < HVYCOK.
2. GHGs are higher with corn starch ethanol than that with corn stover ethanol.
3. GHGs are similar between BR 2 and BR4-T.
4. GHGs decrease in the order of Purchased H_2 >in situ hydrogen > gasification hydrogen.

In 2022, combining the GHG emission results from BAU gasoline and HOF gasoline results in the GHG emissions for BR domestic gasoline pools, shown Figures 9-102 through 9-103. The 2040 results are shown in Figure 9-104.

Compared to the WTW GHG emissions of BR fuels in 2022, the BR set fuels in 2040 have slightly lower GHG emissions, mostly attributable to the decrease in PTW GHG emissions, caused by the increase of bioreformate blended into the domestic gasoline pool (now 100% HOF). In about half of the cases, the WTP GHG emissions decrease in 2040.

The WTW GHG emissions of the BR set fuels produced in configuration refineries compared to GHG emissions of the configuration base case domestic gasolines (E10) are shown in Figures 9-105 through 9-106 for 2022 and 2040, respectively.

In 2022, all the BR set fuels have lower GHG emissions (g/MJ basis) than baselines (with corn starch ethanol), and the reduction benefit is strongly dependent on the hydrogen source for BR production. The process with purchased hydrogen leads to the smallest GHG reduction, about 5% or less, while the process with gasification hydrogen shows the greatest reduction, about 12%. For both BR2 and BR4-T, processes using renewable hydrogen (in-situ and gasification) and corn starch ethanol show greater GHG emission reduction benefits than those using starch ethanol and purchased hydrogen.

In 2040, two sets of baselines are used for comparison: one with ethanol from corn starch and the other with ethanol from corn stover. BR set fuels provide greater GHG reduction benefits in 2040 than in 2022, compared with corresponding baselines, refinery configuration, and ethanol source. BR2/BR2-T and BR4/BR4-T fuels (27 vol% BR blending) produced with renewable hydrogen (in-situ and gasification) also show larger GHG emission reductions (per MJ basis) compared to E set fuels. For example, F19 (with 30% ethanol blending), has the lowest GHG emissions among the E set fuels: 14%–15% reduction with corn stover ethanol and 7-8% reduction with corn starch ethanol. However, BR set fuels produced with in-situ renewable hydrogen show a 14%–18% reduction in GHG emissions and a 19%–22% reduction when produced with gasification H_2.

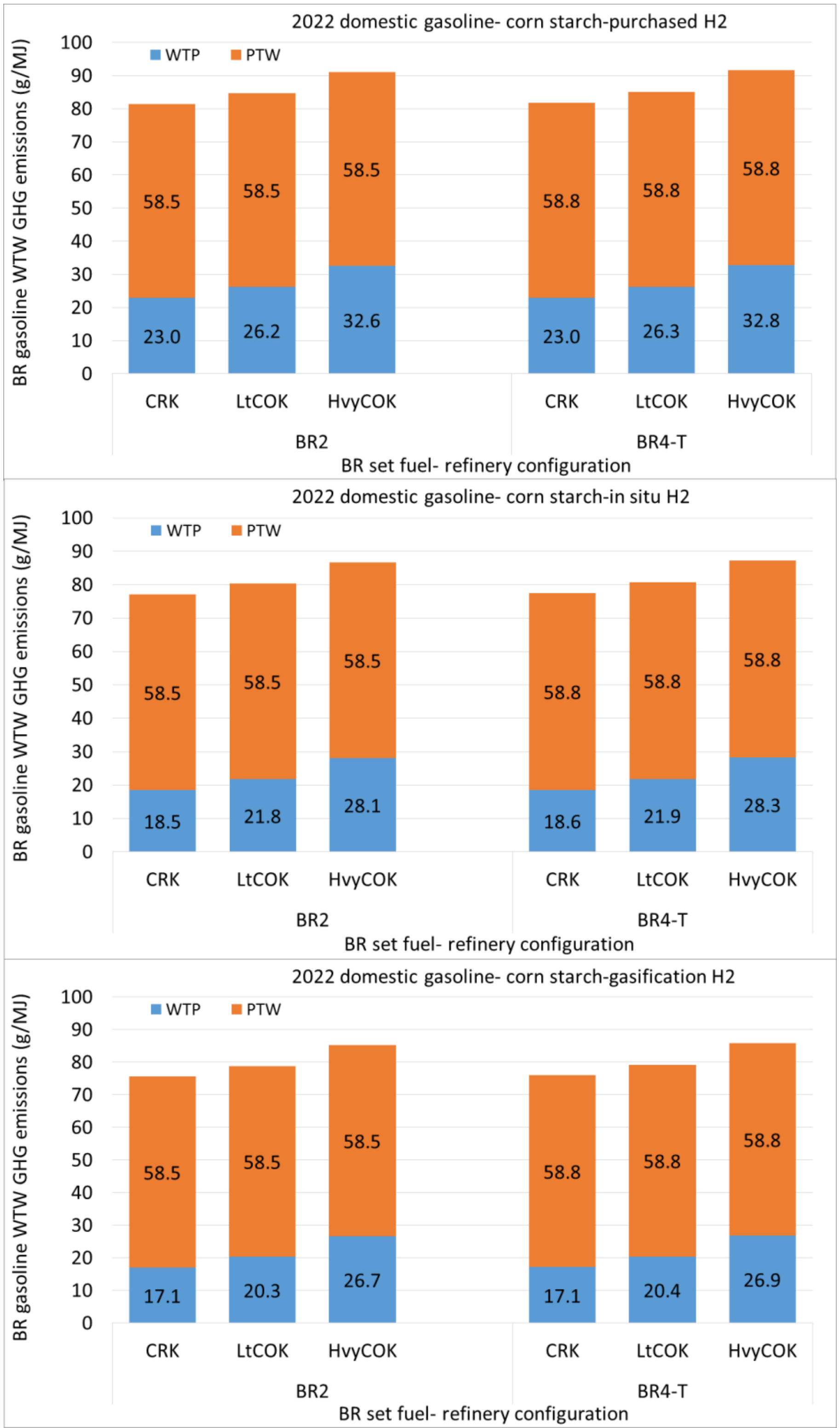


Figure 9-102. Per-MJ WTW GHG Emissions for BR Domestic Finished Gasolines Produced in Configuration Refineries with Ethanol from Corn Starch (in BAU Gasoline) and Bioreformate Using Different Hydrogen Sources in 2022

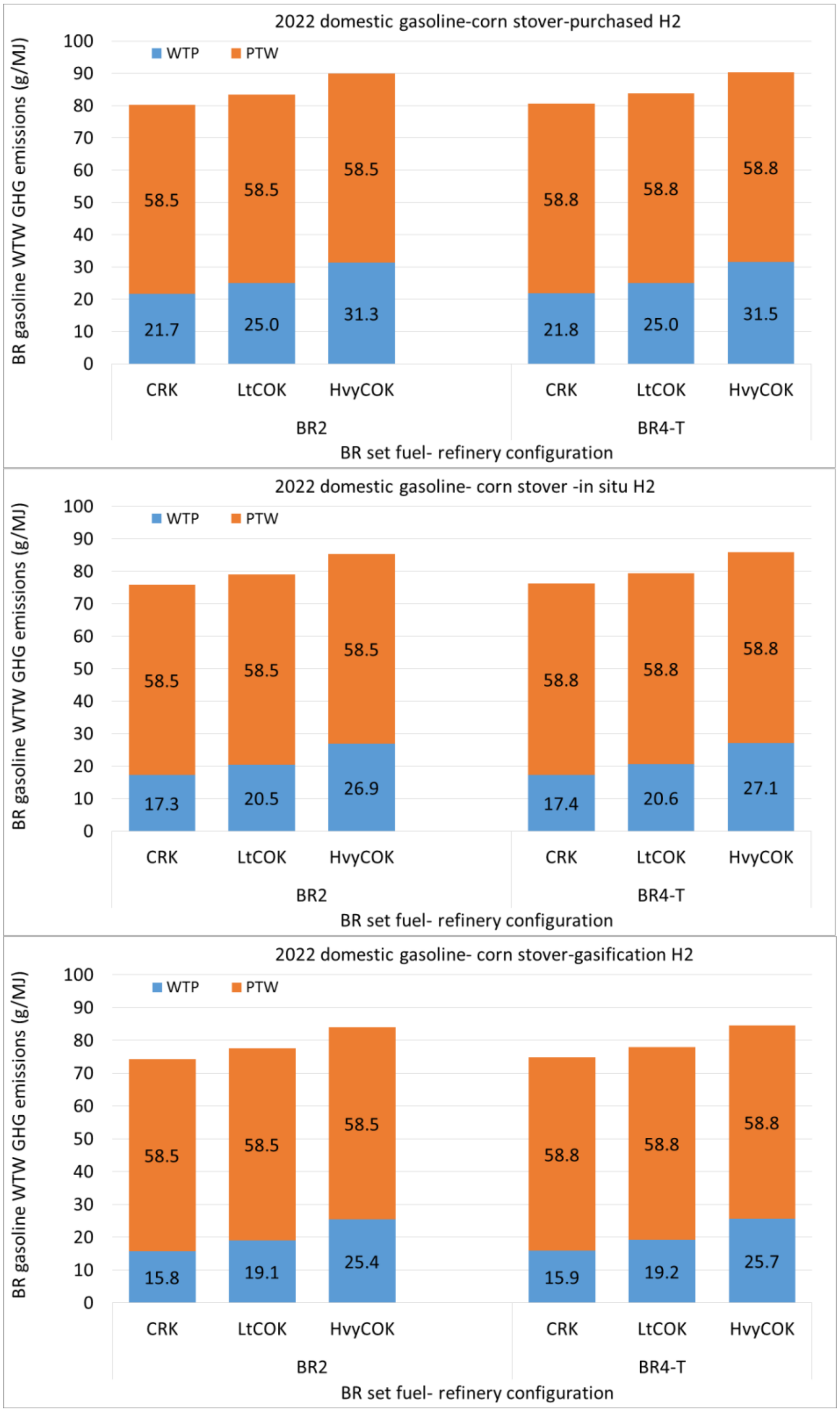


Figure 9-103. Per-MJ WTW GHG Emissions for BR Domestic Finished Gasoline Produced in Configuration Refineries with Ethanol from Corn Stover (in BAU Gasoline) and Bioreformate Using Different Hydrogen Sources in 2022

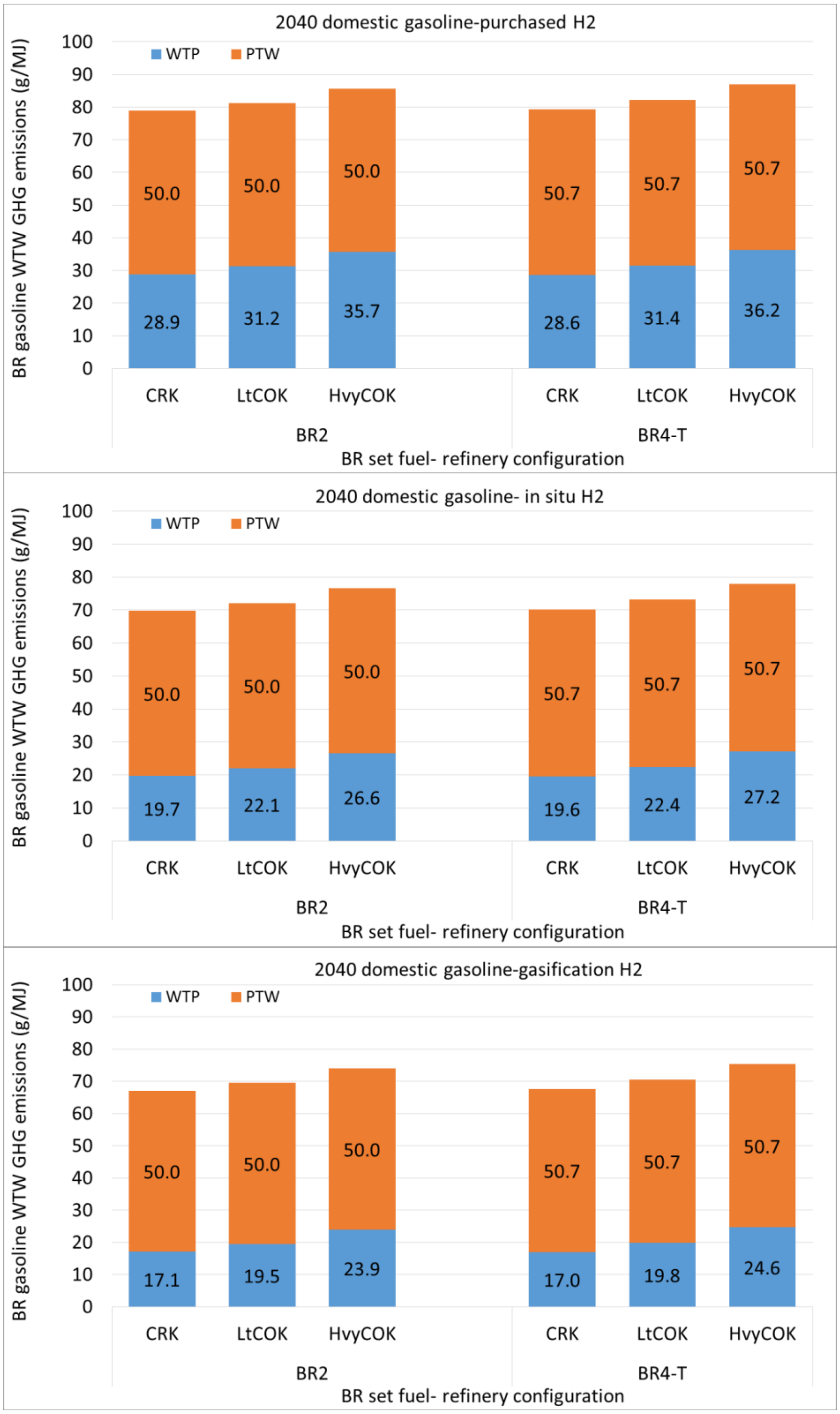


Figure 9-104. Per-MJ WTW GHG Emissions for BR Domestic Gasoline Produced in Configuration Refineries with Bioreformate Using Different Hydrogen Sources in 2040

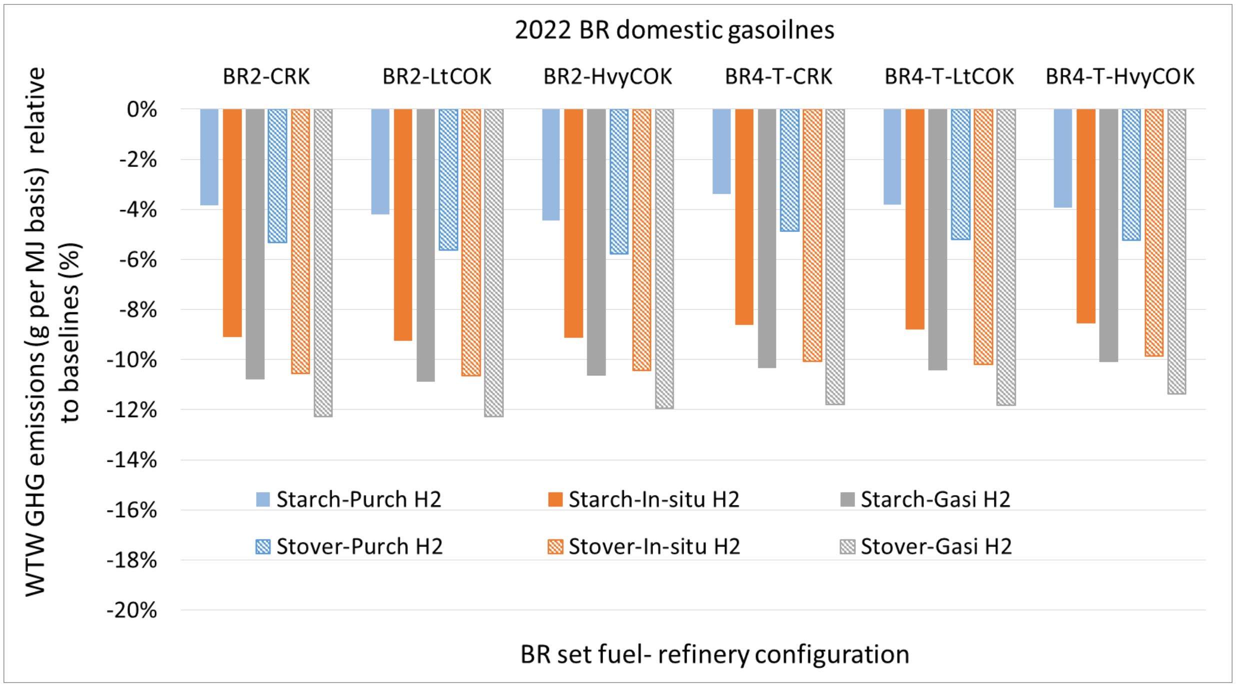


Figure 9-105. Per-MJ Changes in WTW GHG Emissions of Configuration Refinery BR Set Domestic Finished Gasolines (with BAU Gasoline Having Corn Starch Ethanol or Corn Stover Ethanol), Relative to Baselines in 2022. Baselines Use Corn Starch Ethanol

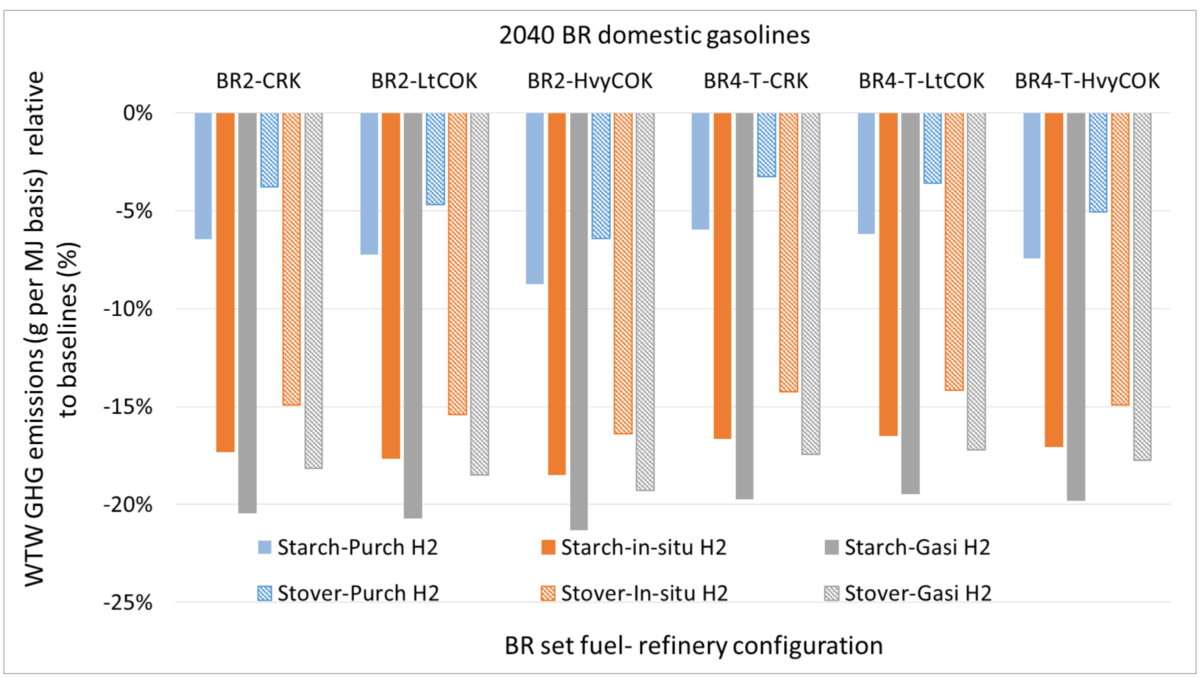


Figure 9-106. Per-MJ Changes in Configuration Refinery BR Set Fuels WTW GHG Emissions with Baselines in 2040

9.2.2.3 Per-Mile WTW Energy Use of BR Fuels from Configuration Refineries

WTW energy use (MJ/mile) for BR fuels in configuration refineries was also calculated on a per-mile basis to account for the benefit of fuel economy gains enabled by high octane number. Figures 9-107 and 9-108 below show the energy use breakdown for BAU gasoline and HOF gasoline, respectively, for year 2022.

BR4-T BAU gasoline has slightly higher total energy use (about 0.07 MJ/mile) than BR2 at the WTP stage. The difference in gasoline production energy intensity was seen in Section 6, where BR4-T was shown to have slightly higher natural gas usage. The energy input for gasoline production is in turn determined by gasoline pool component shares, as shown in Section 5. Cases with corn stover ethanol have total energy use about 0.30 MJ/mile higher than that of corn starch ethanol cases but lower fossil energy use.

HOF gasoline produced with purchased hydrogen has the lowest total energy and petroleum energy use, but the highest fossil energy use. BR production with gasification hydrogen has the lowest fossil energy use.

HOF gasoline energy use varies with different fuel economy with different ON/CR assumptions (although the maximum difference is only 0.12 MJ/mile), and the results are summarized in Tables A4-29 to A4-31 in Appendix 4.

The impact of different ON/CR assumptions on BR HOF gasoline WTW energy use is minor, only about 0.1 MJ/MJ for total energy use, 0.05 MJ/MJ for fossil energy and 0.01%–0.02 MJ/MJ for petroleum energy.

Combined BR domestic finished gasoline pools per-mile WTW energy use values in 2022 and 2040 are shown in Figures 9-109, 9-110 and 9-111. The results are also shown in Tables A4-32 to A4-35 in Appendix 4.

For all cases, the BR production H_2 source has a sizeable impact on BR domestic gasoline WTW energy use: about 0.3–0.4 MJ/MJ for fossil energy use. The refinery configuration also has noticeable impact of 0.15–0.5 MJ/MJ on fossil energy. The impact of ethanol source on BR energy use is minor: about 0.05 MJ/MJ.

From 2022 to 2040, the WTW total energy use increases by 0.7–1.4 MJ/mile depending on refinery configuration, but fossil energy and petroleum energy use decreases by 0.2–0.6 MJ/mile and 0.4–0.5 MJ/mile, respectively. This is because the production of bio-blendstock, ethanol or BR is much more total energy intensive than gasoline BOB production, and the difference cannot be offset by fuel economy gain. Thus, the higher share of bioreformate in 2040 (100% HOF) leads to higher consumption of total energy. At the same time, most bioreformate production (except for corn starch ethanol and BR production with purchased H_2) consumes less fossil energy and less petroleum energy than gasoline BOB production, so the higher level blending leads to lower use of fossil energy and petroleum energy. BR cases with corn starch ethanol and BR production with purchased H_2 show higher fossil and petroleum energy use in the WTP stage in both 2022 and 2040; however, the fuel economy gain in the PTW stage offsets that and leads to a net reduction along the WTW cycle.

Different ON/CR assumptions have only a minor impact on BR domestic gasoline pool energy uses in 2022 and 2040: about 0.04–0.15 MJ/MJ for total energy use, 0.03–0.08 MJ/MJ for fossil energy use, and 0.02–0.05 MJ/MJ for petroleum energy use.

A comparison of BR domestic gasoline energy use to baselines is shown in Figure 9-112 and 9-113.

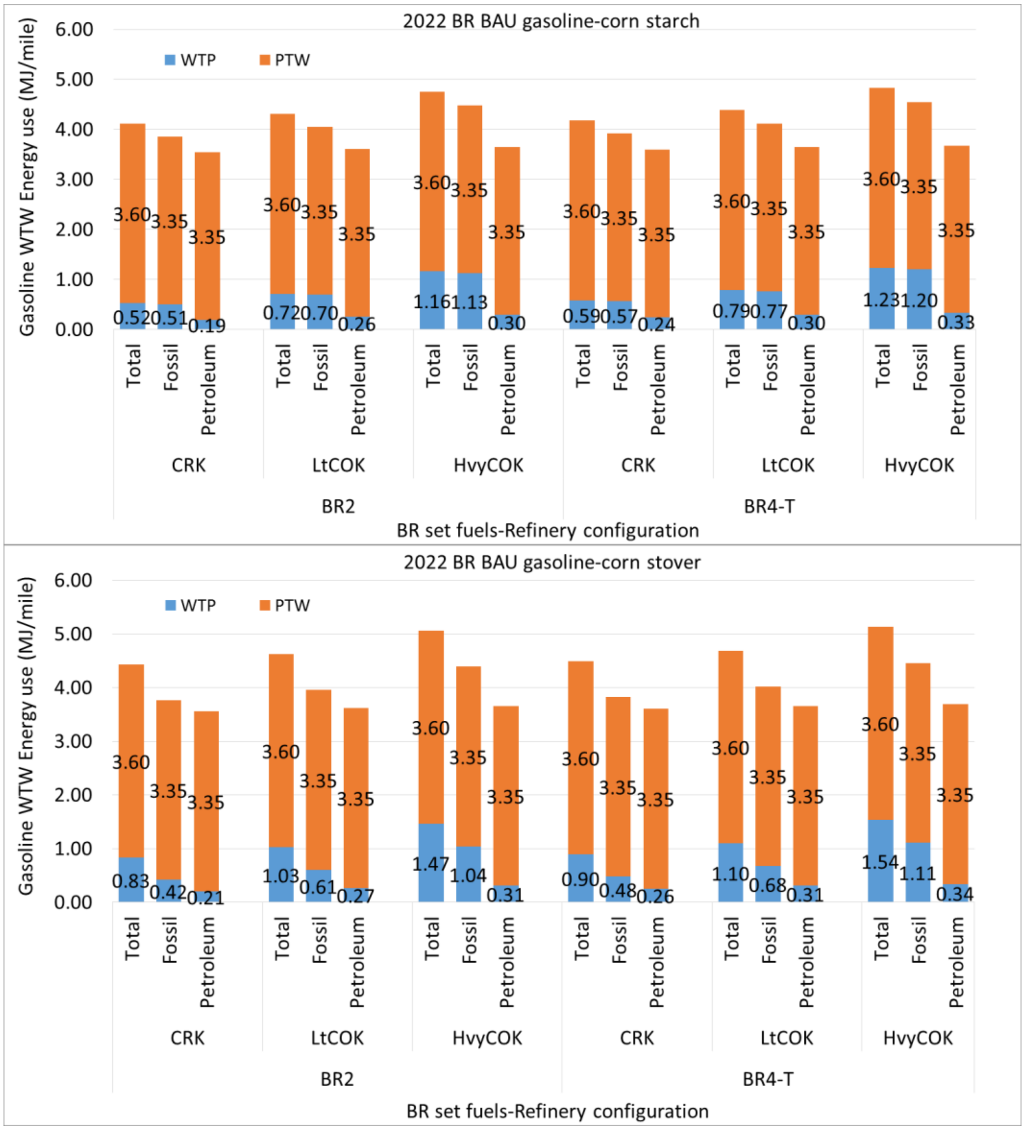


Figure 9-107. Per-Mile WTW Energy Uses for BAU Gasoline Produced in Configuration Refineries with Ethanol from Different Sources, Broken Down by WTP and PTW Stages in 2022

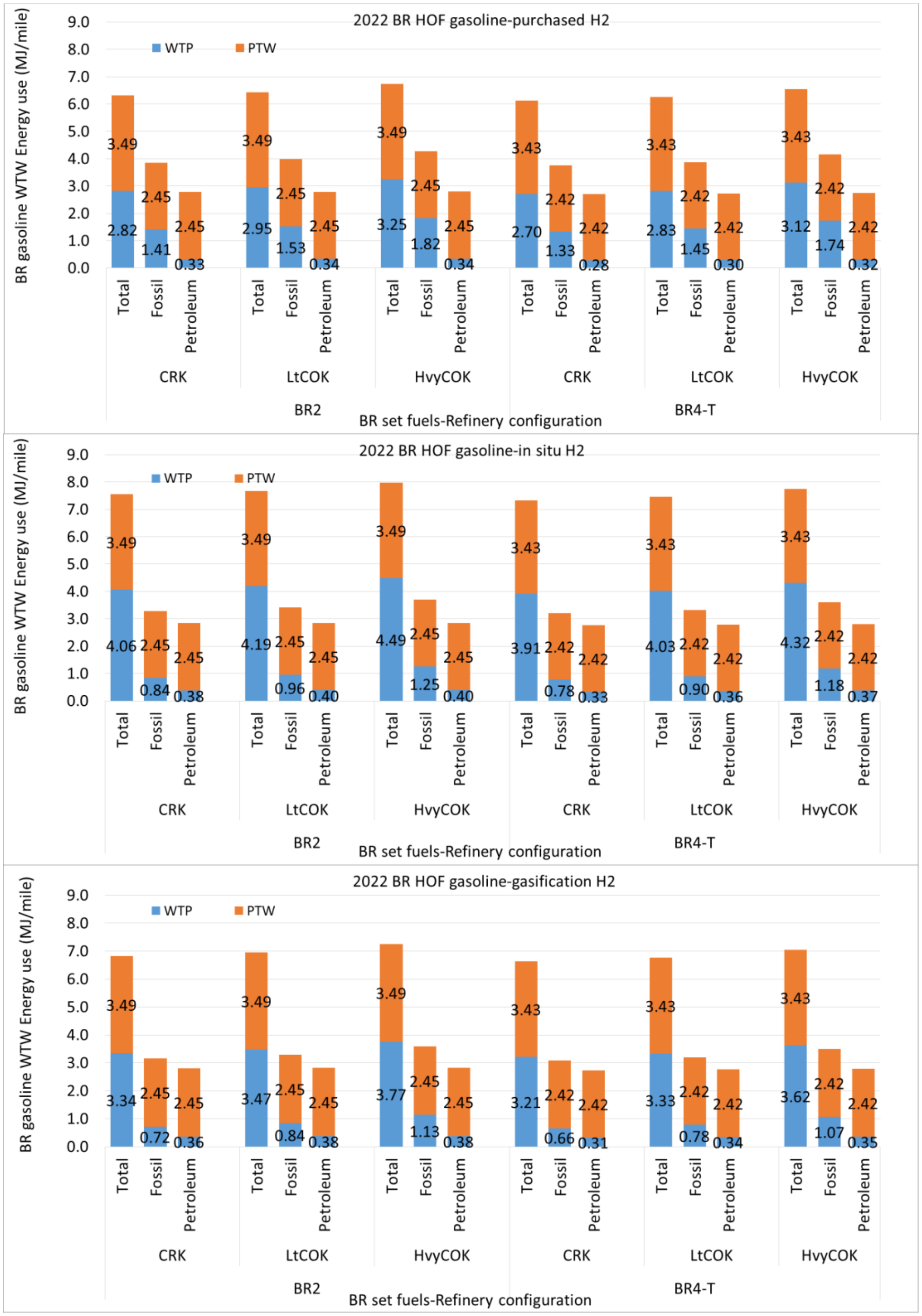


Figure 9-108. Per-Mile WTW Energy Use for HOF Gasoline Produced in Configuration Refineries with Bioreformate Using Different Hydrogen Sources, Broken Down by WTP and PTW Stages in 2022 (for ON/CR of 3.0)

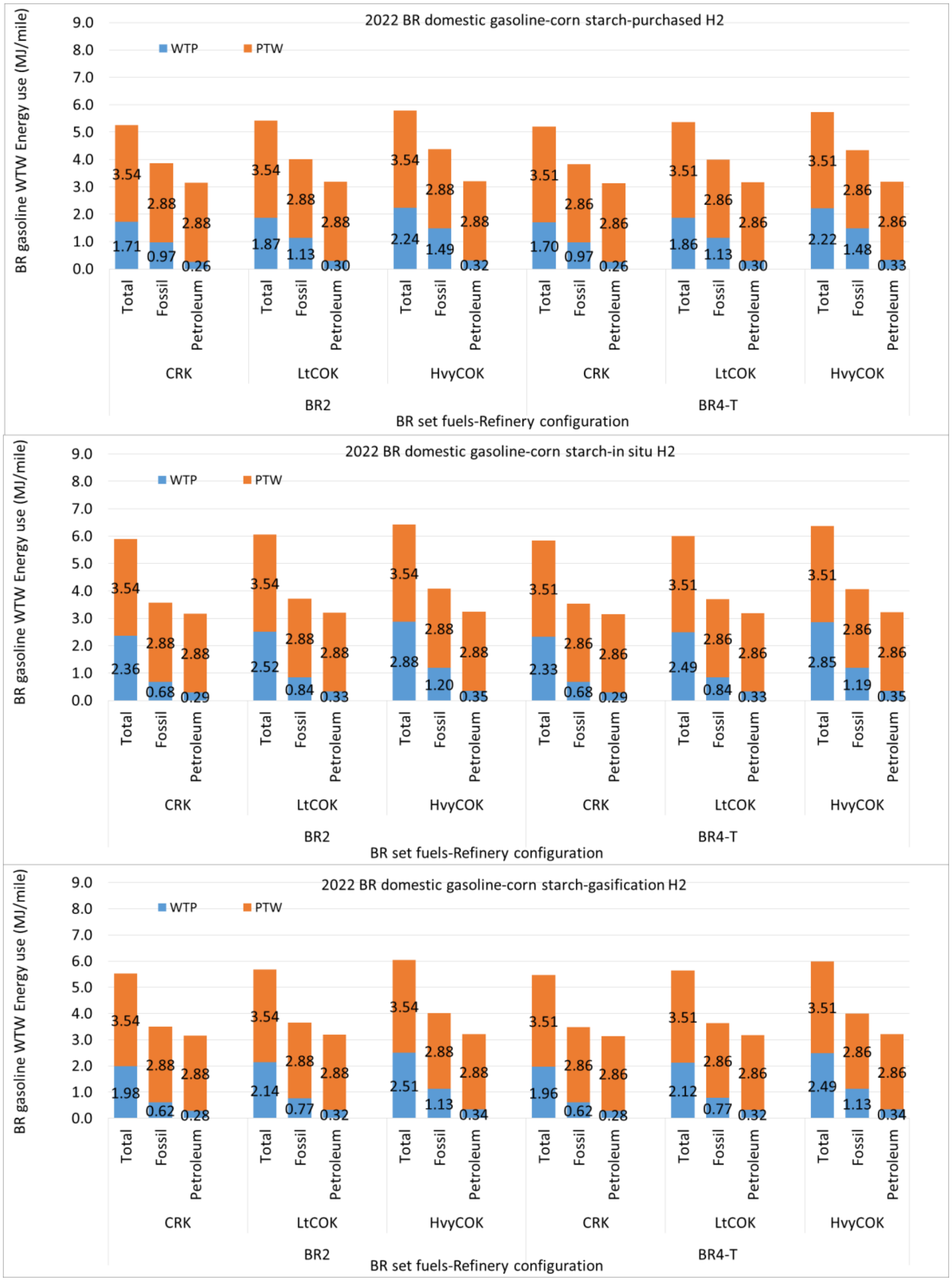


Figure 9-109. Per-Mile WTW Energy Uses for BR Domestic Finished Gasolines Produced in Configuration Refineries with Ethanol from Corn Starch and Bioreformate Using Different Hydrogen Sources in 2022 (for ON/CR of 3.0)

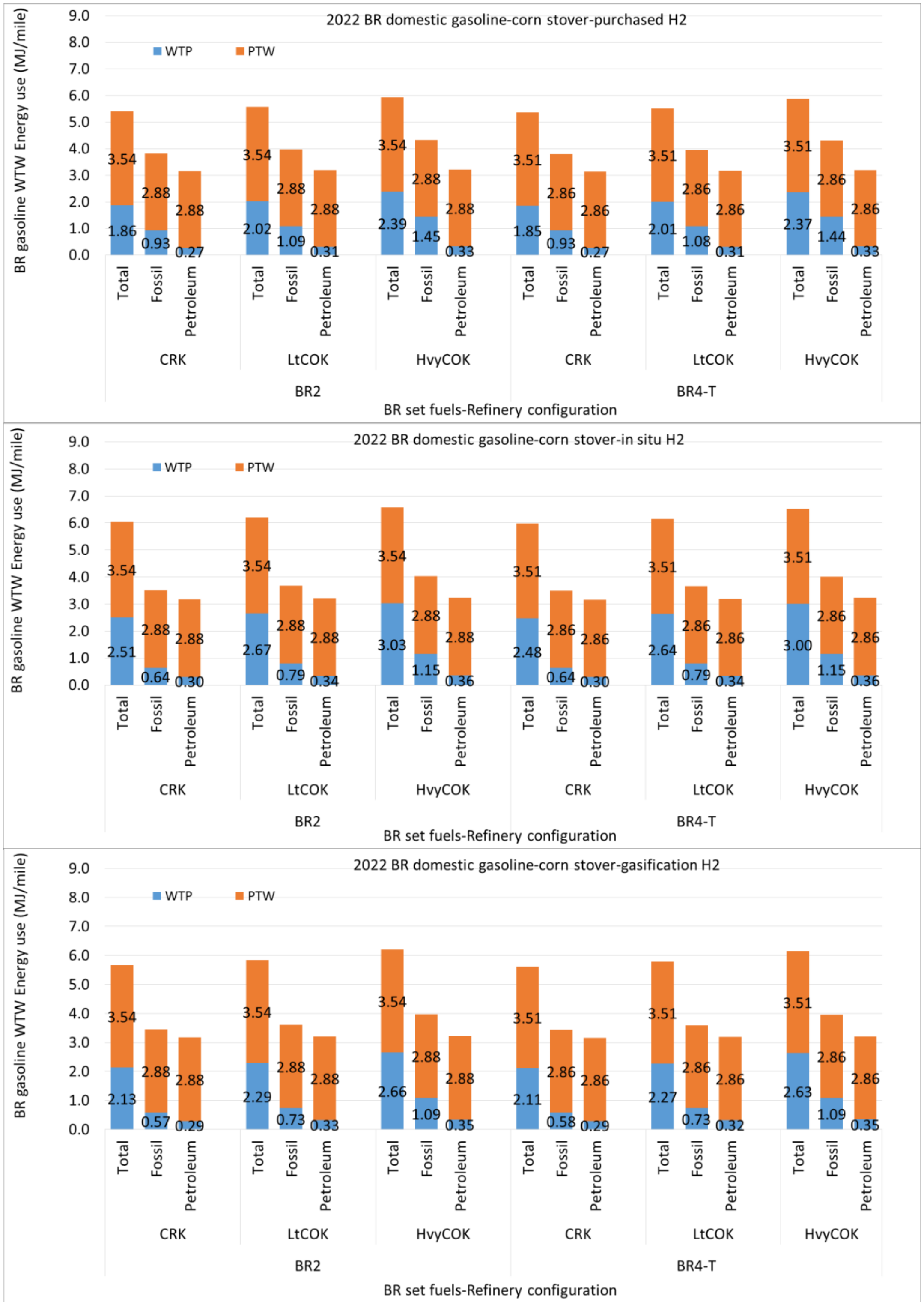


Figure 9-110. Per-Mile WTW Energy Use for BR Domestic Finished Gasolines Produced in Configuration Refineries with Ethanol from Corn Stover and Bioreformate Using Different Hydrogen Sources in 2022 (for ON/CR of 3.0)

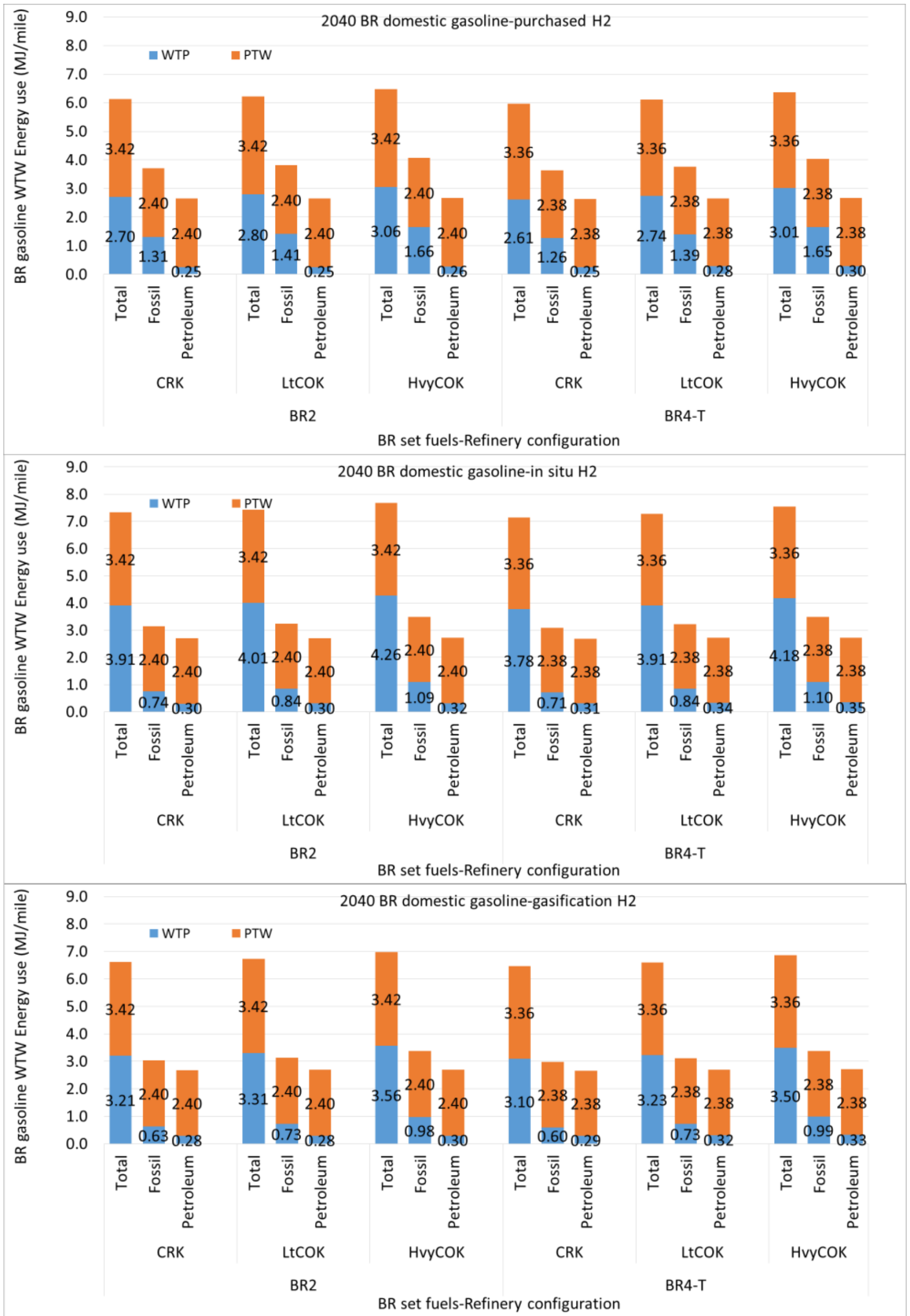


Figure 9-111. Per-Mile WTW Energy Uses for BR Domestic Finished Gasolines Produced in Configuration Refineries With Bioreformate Using Different Hydrogen Sources in 2040 (for ON/CR of 3.0)

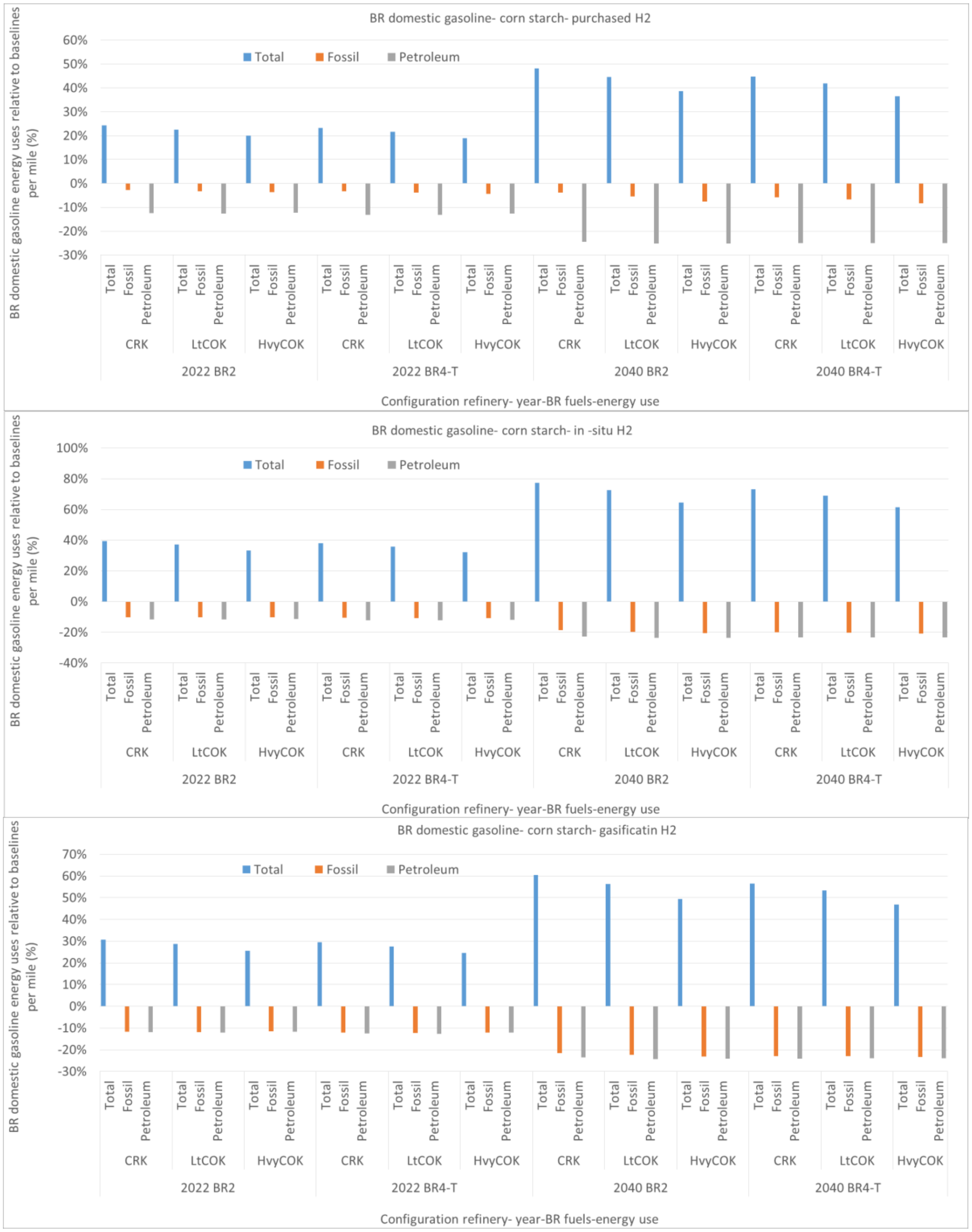


Figure 9-112. Per-Mile Changes in WTW Energy Use for BR Domestic Finished Gasolines Produced in Configuration Refineries Relative to Baselines (for ON/CR of 3.0). In 2022, BAU Gasoline and Baselines Use Corn Starch Ethanol. In 2040, BR Domestic Gasolines Have No Ethanol and Baselines Use Corn Starch Ethanol

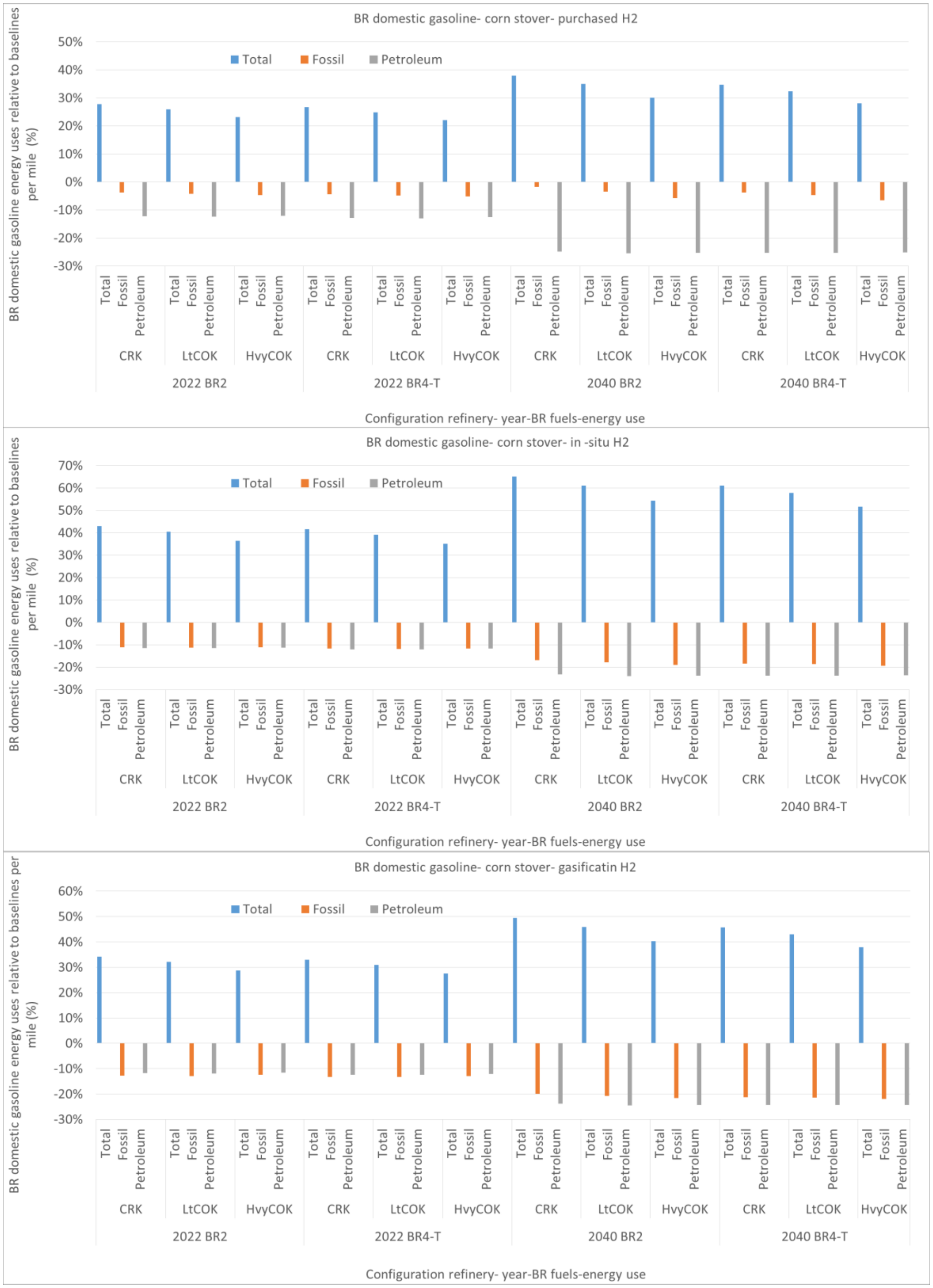


Figure 9-113. Per-Mile Changes in WTW Energy Uses of BR Domestic Finished Gasolines Produced in Configuration Refineries Relative to Baselines (for ON/CR of 3.0). In 2022, BAU Gasolines Use Corn Stover Ethanol and Baselines Use Corn Starch Ethanol. In 2040, BR Domestic Gasolines Have No Ethanol and Baselines Use Corn Stover Ethanol

The following was observed about **per-mile** energy use for BR gasolines with corn starch ethanol in 2022:

- Total energy use for BR2 and BR4-T (both with 27 vol% bioreformate) domestic gasoline pools with purchased hydrogen produced in CRK, LtCOK, and HvyCOK refineries is 22%–28% higher than baselines. However, fossil energy use is reduced 2%–4%, and petroleum energy use is reduced 12%–13%.

- Total energy use for BR2 and BR4-T domestic gasoline pools with in-situ hydrogen is 32-40% higher than baselines. However, fossil energy use is reduced 9-10% and petroleum energy use 11%–12%.

- Total energy use for BR2 and BR4-T domestic gasoline pools with gasification hydrogen is 25%–32% higher than baselines. However, both fossil and petroleum energy use is reduced by 11%–12%.

The results with corn stover ethanol are similar, but with slightly increased total energy use and slightly decreased fossil energy and petroleum energy use.

In 2040, compared with 2040 baselines containing corn starch ethanol, total energy use for BR domestic gasolines with corn starch ethanol increases by 38%–50% for processes using purchased H_2, 60%–80% for in-situ H_2 and 49%–60%, for gasification H_2 cases. All cases show greater reductions in fossil energy use and petroleum energy use than in 2022. Cases with purchased hydrogen show fossil energy use reduced by 3%–8% and petroleum energy use reduced by 24%–25%. For the cases with in-situ hydrogen, fossil energy use is reduced by 18%–20% and petroleum energy by 20%–23%. For cases with gasification hydrogen, fossil energy use is reduced by 21%–23`% and petroleum energy by 23%–24%. BR domestic gasolines with purchased hydrogen show the least fossil energy reduction but the highest petroleum energy reduction, and BR domestic gasolines with gasification hydrogen show the greatest fossil use reduction.

For fossil energy and petroleum energy use, corn stover ethanol cases are similar to corn starch ethanol cases.

BR domestic gasoline energy use with assumptions of 3.7 ON/CR and 5.6 ON/CR are similar to those assuming 3.0 ON/CR and are not discussed here for brevity.

9.2.2.4 Per-Mile WTW GHG Emissions of BR Fuels from Configuration Refineries

WTW GHG emissions for BR set fuels produced in configuration refineries were also evaluated on a per-mile basis. For 2022, GHG emissions were evaluated in several aspects: refinery configuration for BOB production, BR production with different hydrogen sources, ethanol sources, and fuel economy estimates.

In 2022, the BAU gasoline GHG emissions per mile vary with the refinery configuration and ethanol source. The results, broken down into WTP and PTW stages, are shown in Figure 9-114.

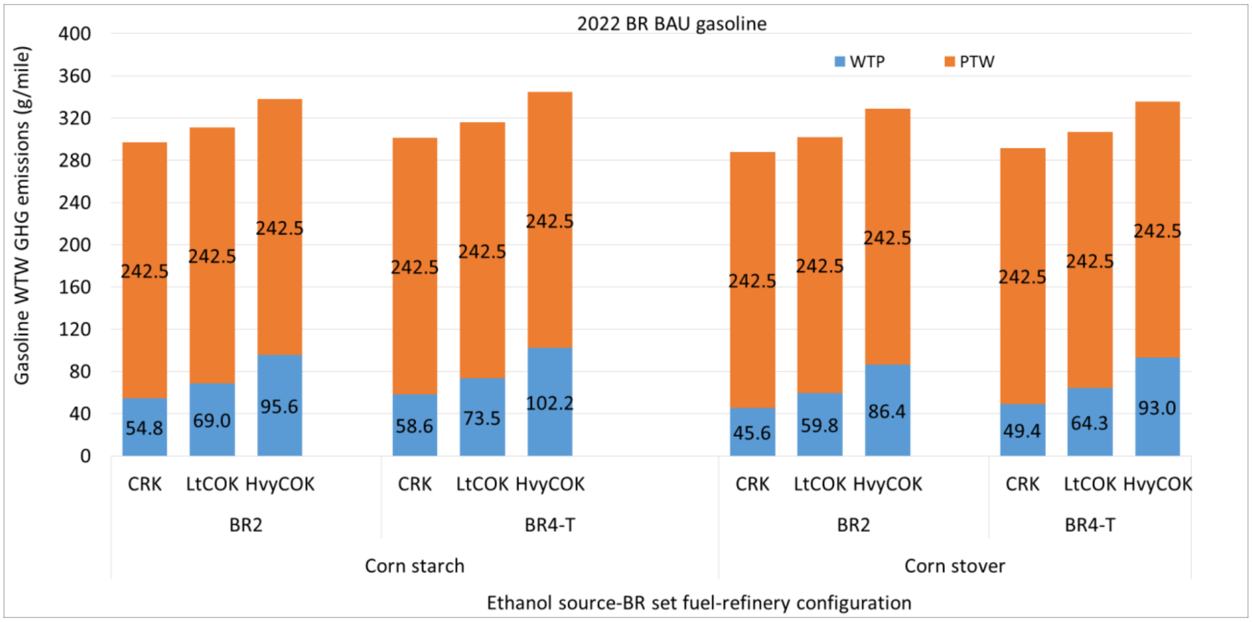


Figure 9-114. Per-Mile WTW GHG Emissions of BR Set BAU Gasoline with Corn Starch Ethanol and Corn Stover Ethanol in Configuration Refineries (for ON/CR of 3.0)

In 2022, with increasing refinery complexity, the BAU gasoline GHG emissions increase sharply for the WTP stage by about 15–45 g/mile, but the changes comprise a smaller fraction of the overall WTW lifecycle as they are combined with the higher PTW emissions. BR2 BAU gasoline has higher GHG emissions than BR4-T BAU gasoline. With 10% ethanol blending, BAU gasoline GHG emissions vary by 9–10 g/mile with different ethanol sources, with the lower values for corn stover.

In 2022, the HOF gasoline GHG emissions per mile vary with the refinery configuration, hydrogen source for bioreformate production and fuel economy. The results, broken down into WTP and PTW stages, are shown in Figure 9-115.

In 2022, with 27 vol% bioreformate blending in HOF gasoline, the impact of different hydrogen sources on BR HOF gasoline WTW GHG emissions is pronounced: there is a difference of about 30–40 g/mile, between purchased hydrogen (fossil source) and renewable hydrogen (in-situ H_2 or gasification H_2). The HOF gasoline GHG emissions increase with increasing refinery complexity, with a difference about 8–28 g/mile. The RON has a lesser impact on the WTW GHG emissions; the difference between BR2 HOF gasoline and BR4-T HOF gasoline is about 5–7 g/mile. The different fuel economy with varying ON/CR assumptions has only a very minor effect on BR domestic gasoline WTW GHG emissions: about 1–2 g/mile, shown in the Table 9-16.

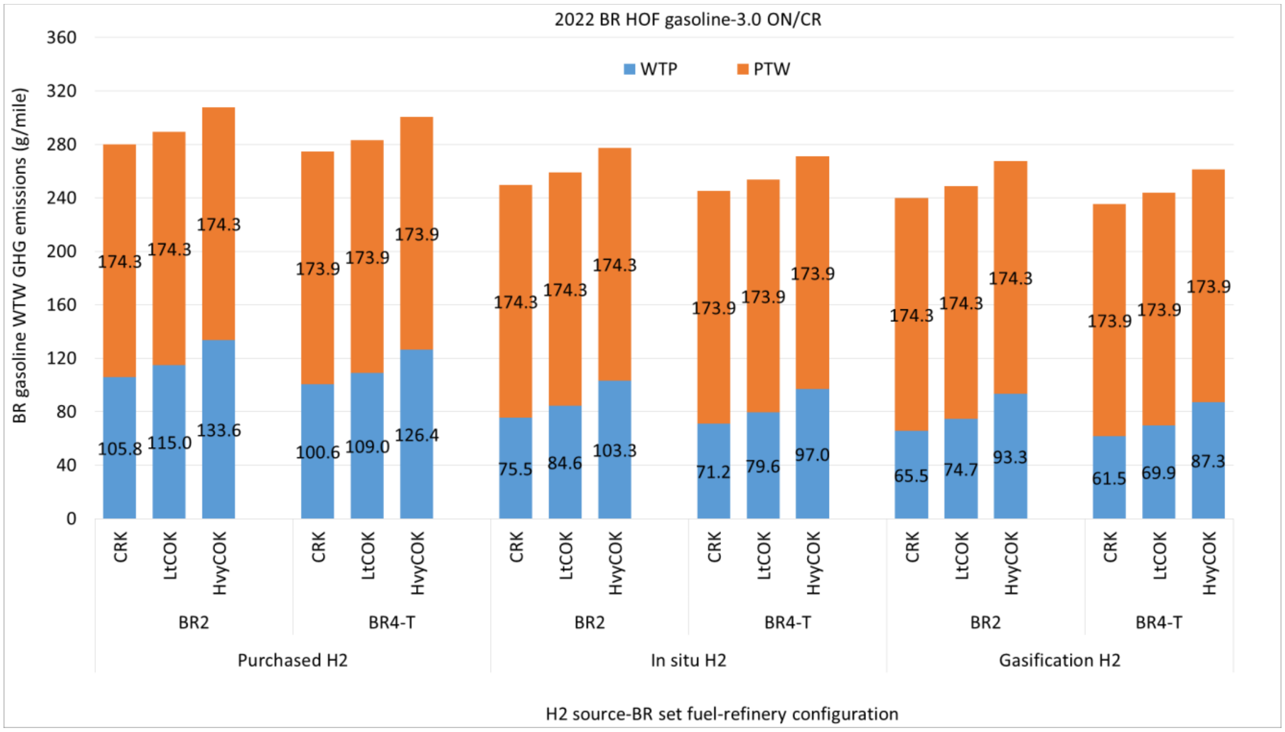


Figure 9-115. Per-Mile WTW GHG Emissions of BR Set HOF Gasoline Produced in Configuration Refineries with Various Hydrogen Sources in 2022 (for ON/CR of 3.0)

Table 9-16. WTW GHG Emissions for BR Set HOF Gasoline Produced in Configuration Refineries with Various Hydrogen Sources and Varying Fuel Economy Assumptions in 2022

			3.0 ON/CR (g/mile)		3.7 ON/CR (g/mile)		5.6 ON/CR (g/mile)	
H_2 Source	Fuel	Configuration	WTP	PTW	WTP	PTW	WTP	PTW
Purchased H_2	BR2	CRK	105.8	174.3	106.5	175.4	107.5	177.0
		LtCOK	115.0	174.3	115.7	175.4	116.7	177.0
		HvyCOK	133.6	174.3	134.5	175.4	135.7	177.0
	BR4-T	CRK	100.6	173.9	101.3	175.1	102.5	177.2
		LtCOK	109.0	173.9	109.7	175.1	111.1	177.2
		HvyCOK	126.4	173.9	127.3	175.1	128.8	177.2
In-situ H_2	BR2	CRK	75.5	174.3	76.0	175.4	76.7	177.0
		LtCOK	84.6	174.3	85.2	175.4	85.9	177.0
		HvyCOK	103.3	174.3	104.0	175.4	104.9	177.0
	BR4-T	CRK	71.2	173.9	71.7	175.1	72.6	177.2
		LtCOK	79.6	173.9	80.1	175.1	81.1	177.2
		HvyCOK	97.0	173.9	97.6	175.1	98.8	177.2

Table 9-16 (Cont.)

H_2 Source	Fuel	Configuration	3.0 ON/CR (g/mile) WTP	3.0 ON/CR (g/mile) PTW	3.7 ON/CR (g/mile) WTP	3.7 ON/CR (g/mile) PTW	5.6 ON/CR (g/mile) WTP	5.6 ON/CR (g/mile) PTW
Gasification H_2	BR2	CRK	65.5	174.3	66.0	175.4	66.6	177.0
		LtCOK	74.7	174.3	75.1	175.4	75.8	177.0
		HvyCOK	93.3	174.3	93.9	175.4	94.8	177.0
	BR4-T	CRK	61.5	173.9	62.0	175.1	62.7	177.2
		LtCOK	69.9	173.9	70.4	175.1	71.2	177.2
		HvyCOK	87.3	173.9	87.9	175.1	89.0	177.2

The WTW GHG emissions of the BR domestic gasoline pools (combining BAU gasoline and HOF gasoline) in configuration refineries are shown in Figures 9-116 and 9-117 below.

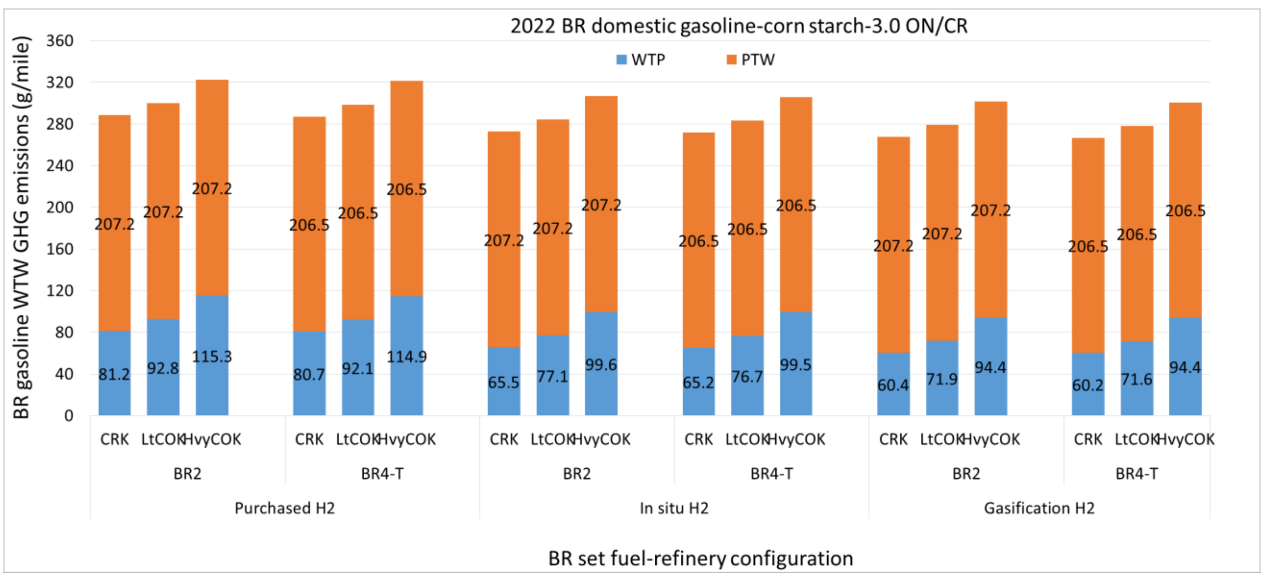


Figure 9-116. Per-Mile WTW GHG Emissions for BR Set Fuels Produced in Configuration Refineries with BAU Gasoline Ethanol from Corn Starch and HOF Gasoline Bioreformate Using Various Hydrogen Sources in 2022 (for ON/CR of 3.0)

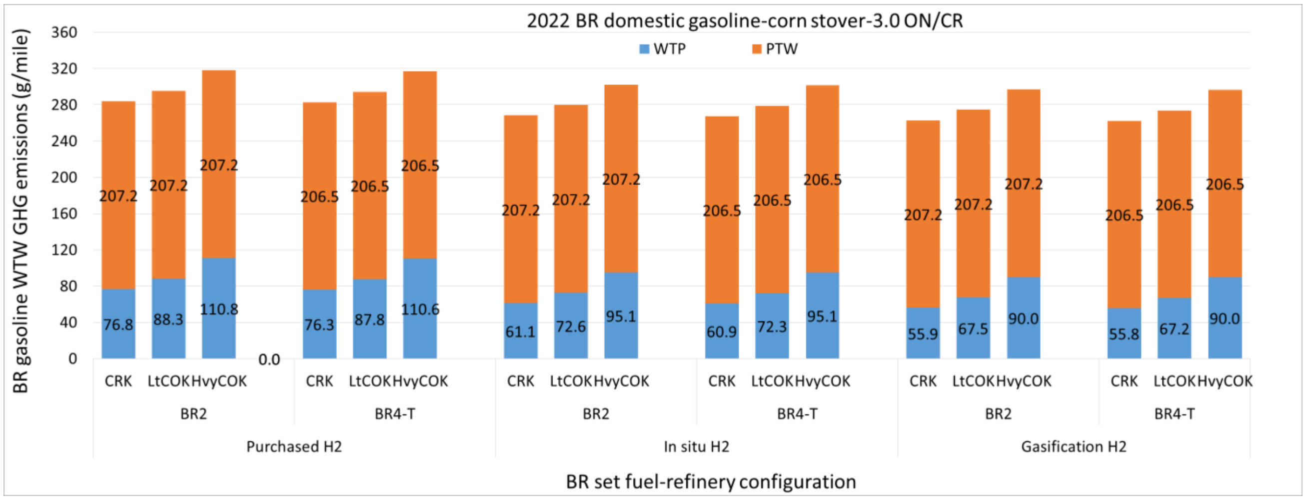


Figure 9-117. Per-Mile WTW GHG Emissions for BR Set Fuels Produced in Configuration Refineries with BAU Gasoline Ethanol from Corn Starch and HOF Gasoline Bioreformate Using Various Hydrogen Sources in 2022 (for ON/CR of 3.0)

For both sets of results with different ethanol sources, BR2 has slightly higher GHG emissions than BR4-T owing to the higher fuel economy of the latter with its higher RON. The differences of BR domestic gasoline GHG emissions with different ethanol sources are small, about 5 g/mile, owing to 10 vol% ethanol blending for only half of the domestic gasoline pool (5 vol% overall for the domestic gasoline pool).

From 2022 to 2040, the GHG emissions of BR domestic gasolines decrease, owing to the 12% fuel economy gains during this period. The GHG emissions differences caused by different BR production hydrogen sources are about 30–40 g/mile, while the difference caused by different refinery configurations is about 10–20 g/mile. See Figure 9-118.

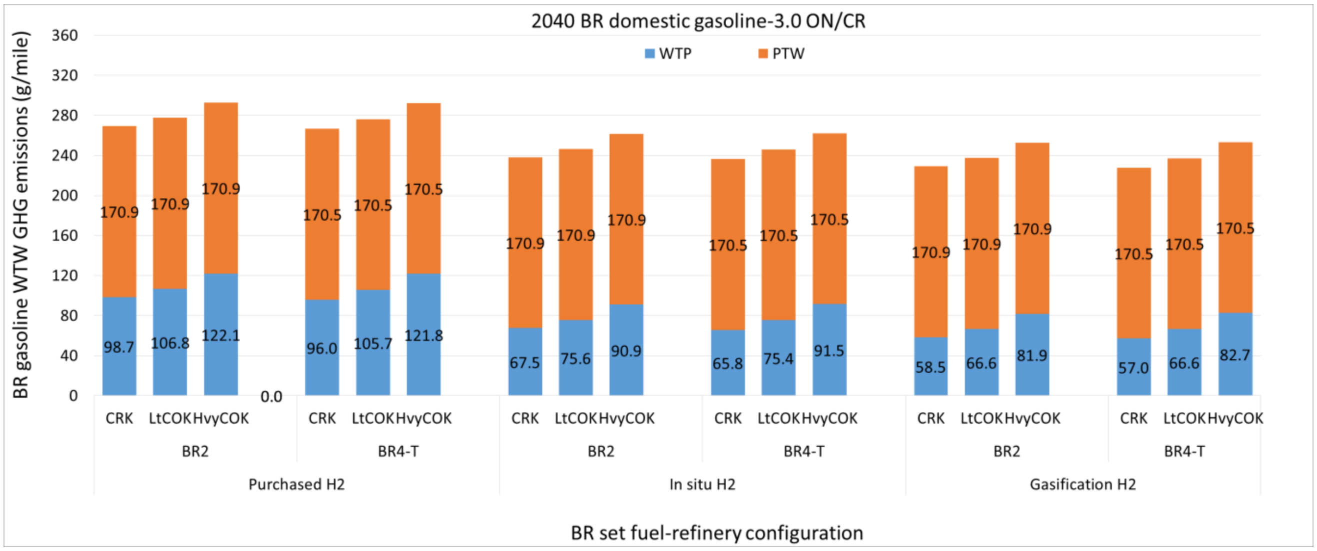


Figure 9-118. Per-Mile WTW GHG Emissions for BR Set Fuels Produced in Configuration Refineries with Bioreformate Produced Using Various Hydrogen Sources in 2040 (for ON/CR of 3.0)

The GHG emissions results of BR domestic gasolines with different ON/CR assumptions are shown in Appendix 4 in Tables A4-36 to A4-38.

The 2022 BR set fuels GHG emissions per mile are compared with baselines in Figure 9-119. BR set fuels with gasification hydrogen have the largest GHG emission reductions, reaching 11%–13% for all the refinery configurations and both ethanol sources in BAU gasoline. BR set fuels with ethanol from corn stover have slightly greater GHG reduction benefits compared to baseline. As stated before, compared to baseline, the GHG emissions increase with increasing refinery complexity, and decrease with ethanol from corn stover in BAU gasoline.

A comparison of BR domestic gasoline pool GHG emissions with baselines in 2040 is shown in Figure 9-120. It is worth noting that although the BR set fuels GHG emissions are not dependent on ethanol source as the HOF share increases to 100%, the baseline still depends on the ethanol source. Decreases relative to baseline values are greater for corn starch rather than corn stover ethanol.

As expected, the reductions in GHG emissions by BR production using gasification hydrogen relative to baseline are the highest. In 2040, with 100% HOF share, different ON/CR estimates have an impact of 1–2 g/mile, or about 0.5%–1%, on the BR set fuel per-mile WTW GHG emissions. In 2040, GHG emission reductions are much larger than in 2022, reaching 5%–12% for fuels produced with purchased hydrogen, 16%–21% with in-situ hydrogen and 19%–23% with gasification hydrogen.

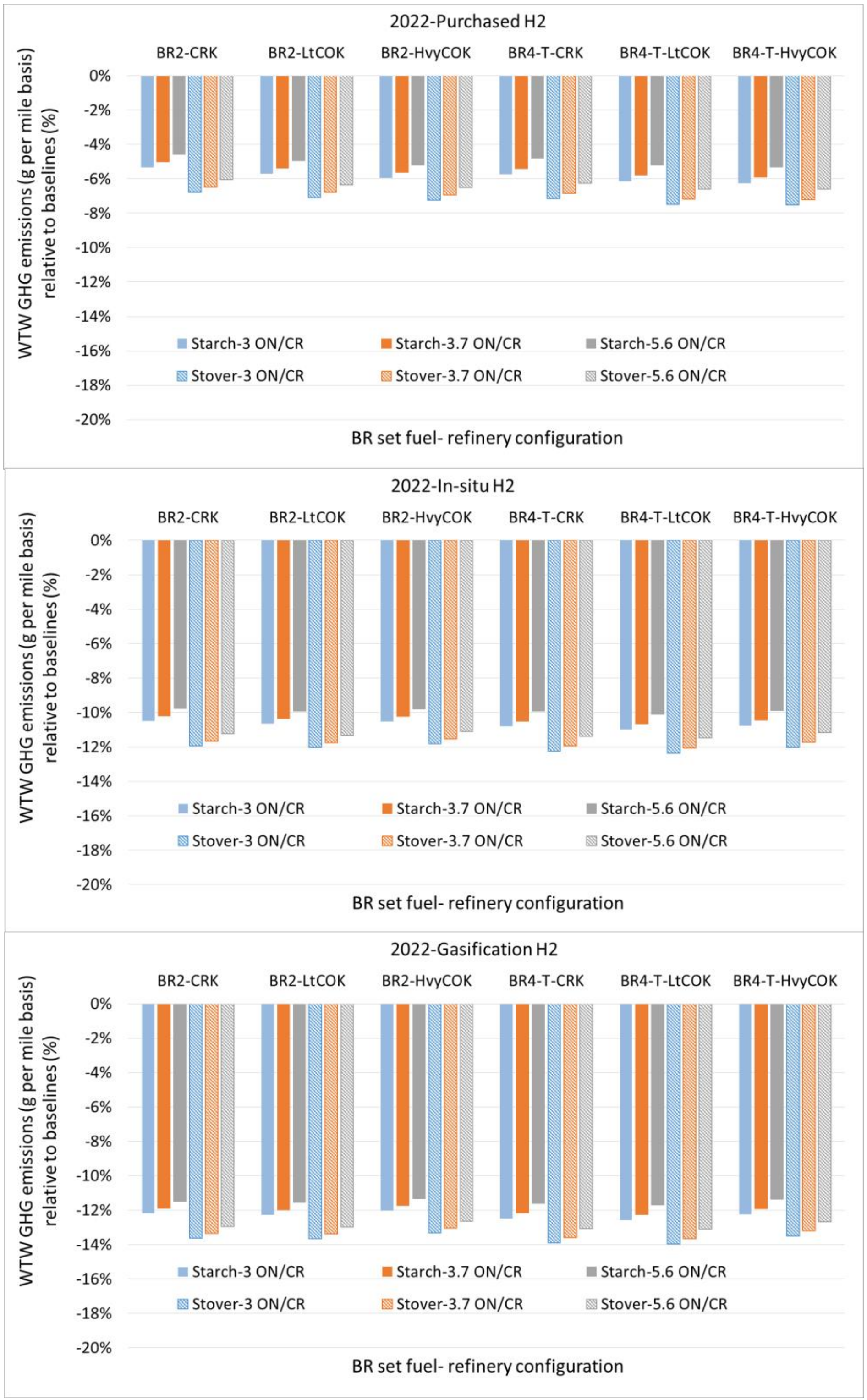


Figure 9-119. Per-Mile Changes in BR Set Fuels WTW GHG Emissions Relative to Baselines (for ON/CR of 3.0) in Configuration Refineries. BAU Gasolines Use Ethanol from Different Sources and HOF Gasolines Use Bioreformate Produced from Different Hydrogen Sources. Baselines Use Corn Starch Ethanol

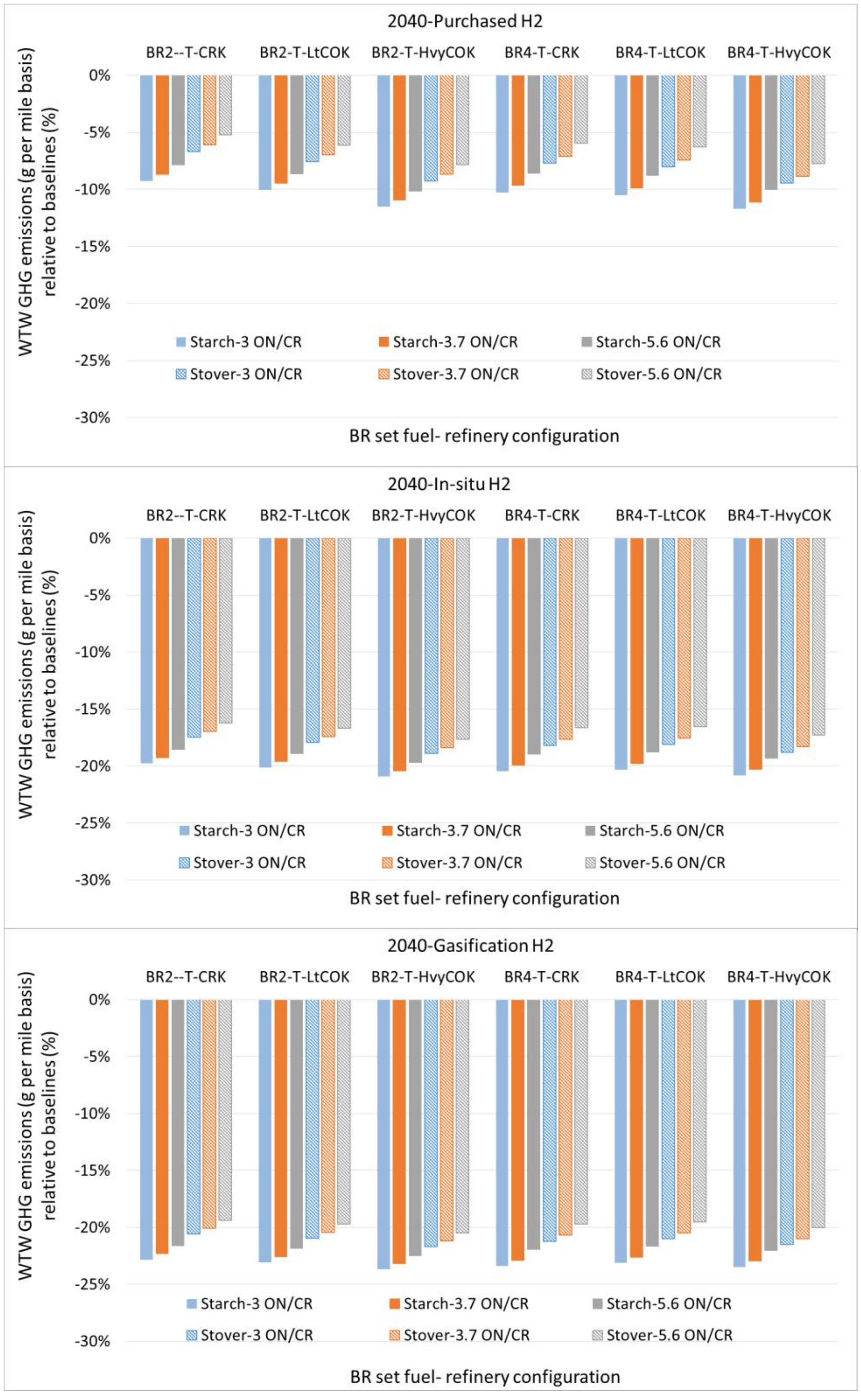


Figure 9-120. Per-Mile Changes in BR Set Fuels WTW GHG Emissions Relative to Baselines (for ON/CR of 3.0, with Bioreformate Produced Using Different Hydrogen Sources. BR Set Fuels Have No Ethanol. Dual Sets of Baselines Used with Corn Starch Ethanol and Corn Stove Ethanol

10. Summary and Conclusions

This report documents ANL's WTW analysis on behalf of U.S.DRIVE, involving energy use and GHG emissions for bio-blended high-octane fuels. The major WTW stages are: crude recovery/transportation, refining process to gasoline, corn/corn stover growing/collection/transportation, ethanol production/transportation, bioreformate production, gasoline transportation and distribution, and vehicle operation.

Petroleum refinery LP modeling was conducted with PADD aggregate models and refinery configuration models to identify and quantify likely refinery changes needed to produce the HOFs. The goal of the refinery LP modeling was setto maximize refinery economic margin for the given set of constraints, not to minimize energy consumption or GHG emissions (these are outputs calculated from the optimal margin solution). In general, the LP modeling was constrained to existing refinery operations and did not include an option for additional investment to overcome infeasibility. For the feasible cases of LP modeling, simulated petroleum refinery energy and GHG results from Jacobs Consultancy's LP modeling were processed and incorporated into the GREET model for WTW analysis of HOFs and vehicle operations with them.

Following are the key observations and conclusions derived from this study.

LP Modeling Results (Sections 5 and 6)

1. To produce the E set and BR set fuels included in this study, LP models were calibrated to meet the RON target but allow MON to float with minimum limit of 82. In LP modeling, the impact of OS could not be simulated for all fuels, as LP modeling was not able to yield gasolines with the desired low OS, which would require low reformate presence in gasoline pool. As a result, some E set fuels from LP modeling have higher aromatic content than the target fuels (which was physically prepared and tested for engine performance). This has minor impact on vehicle operation, as knock-limited engine performance is primarily influenced by RON.

2. The feasibility of producing the various HOFs under various refinery models is summarized in Tables 10-1 and 10-2 below.

3. As shown in Tables 10-1 and 10-2, for certain cases, LP modeling cannot find feasible solutions, indicating that under current refinery configurations and with the mandatory blending content, refineries cannot produce a sufficient volume of BOB that enables the blended streams to meet regulatory specifications and targeted high octane numbers for finished fuels. Infeasible cases were more prevalent in California, due to the high market share of RFG (with its more stringent RVP specifications), compared with PADD 3 and PADD 2 (88% vs 12%), and California-specific limits on specific high-octane hydrocarbons in gasoline, such as aromatics.

Table 10-1. Summary of PADD LP Modeling Cases with Feasible Solutions

Year	2022			2040		
Region	PADD 2	PADD 3	CA	PADD 2	PADD 3	CA
Base Cases	F	F	F	F	F	F
Fuel 01 E10 Low RON	N/A	F	F	N/A	F	F
Fuel 07 E10 Hi RON	N/A	F	F	N/A	IF	IF
Fuel 10 E10 Low RON	N/A	F	F	N/A	F	F
Fuel 14 E10 Mid RON	N/A	F	F	N/A	F	F
Fuel 15 E30 Mid RON	N/A	F	F	N/A	F	F*
Fuel 16 E10 Hi RON	N/A	F	IF	N/A	IF	IF
Fuel 18 E20 Hi RON	N/A	F	F	N/A	F	F*
Fuel 19 E30 Hi RON	N/A	F	F	N/A	F	F*
Fuel 20 E20 Mid RON	N/A	F	F	N/A	F	F*
BR1 9% Bio Mid RON	F**	F	IF	IF	IF	IF
BR2 27% Bio Mid RON	F	F	IF	F	F	IF
BR3 9% Bio Hi RON	F**	F**	IF	IF	IF	IF
BR4 27% Bio Hi RON	F**	F**	IF	F**	F**	IF

F: feasible without refinery investment.
IF: infeasible.
N/A: not applicable.
* Would require CA change of regulations to allow higher than 10 vol.% ethanol.
** These would require a lighter bioreformate (such as toluene) than the bioreformate surrogate produced for the engine study for the U.S.DRIVE.

Table 10-2. Summary of Configuration LP Modeling Cases with Feasible Solutions

	Configuration 2022				Configuration 2040			
	CRK	LTCOK	HVY-COK	COK-HCK	CRK	LTCOK	HVY-COK	COK-HCK
Base Cases	F	F	F	F	F	F	F	F
Fuel 01 E10 Low RON	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fuel 07 E10 Hi RON	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fuel 10 E10 Low RON	F	F	F	F	F	F	F	F
Fuel 14 E10 Mid RON	F	F	F	F	F	F	F	IF
Fuel 15 E30 Mid RON	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Fuel 16 E10 Hi RON	IF	IF	IF	IF	IF	IF	IF	IF
Fuel 18 E20 Hi RON	F	F	F	F	F	F	F	F
Fuel 19 E30 Hi RON	F	F	F	F	F	F	F	F
Fuel 20 E20 Mid RON	F	F	F	F	F	F	F	F
BR1 9% Bio Mid RON	IF	IF	IF	IF	IF	IF	IF	IF
BR2 27% Bio Mid RON	F	F	F	F	F**	F**	F**	F**
BR3 9% Bio Hi RON	IF	IF	IF	IF	IF	IF	IF	IF
BR4 27% Bio Hi RON	F**	F**	F**	IF	F**	F**	F**	IF

Note: See footnotes for Table 10-1.

4. Some modeling cases for E10 fuels with mid or high RON, Fuel 7 (E10, high RON 101, low sensitivity of 8), Fuel 14 (E10, Mid RON 97), and Fuel 16 (E10, high RON 101, high sensitivity of 12) were not feasible due to their high RON requirement but low ethanol blending level, which would force refineries to produce higher-RON BOBs. Although technically feasible solutions were found for many of the higher RON, higher ethanol E set fuels (20%–30% ethanol), from a regulatory standpoint blends containing higher than 10% ethanol are not currently allowed in some states such as California and New York.

5. Many BR set fuel cases were not feasible without investment (in fact, none were feasible in CA). Although the BR stream has the desired high RON, it causes finished BR blended fuels to hit the maximum T90 specification, because of the high boiling point of the BR stream. Simulation of the bioreformate blendstock as toluene resulted in feasible solutions for many of the infeasible BR fuel cases.

6. LP modeling results show that compared to base case E10 BOB production, production of BOBs for HOF blending leads to changes in refinery operations, gasoline components, and exported gasoline shares. Overall refinery energy efficiency varies with production of different bio-blended fuels. For each refinery case, gasoline production energy intensity and efficiency differ for regular E10 gasoline, HOF gasoline and exported gasoline.

7. In the LP modeling of aggregate refineries, PADD 2 aggregate refinery is set to processes a large amount of energy-intensive oil sands, as projected in EIA's Annual Energy Outlook. The modeled CA refinery shows a high hydrogen demand, which drives up natural gas use in the SMR process.

8. For configuration refineries, LP modeling showed that with increasing refinery complexity (in the order of cracker to light coker to heavy coker and to coker-hydro-treater), the reformer contribution (reformate volume × reformer severity) decreases and the hydrogen demand increases significantly. This corresponds to the increased use of high-sulfur, low-API crude oil in the more complex refineries.

9. For both 2022 and 2040, the base case domestic gasoline pools in PADD 2 and PADD 3 are projected to mainly consist of FCC and reformate. In addition to those two key gasoline components, the CA base case gasoline pool includes a good amount of alkylate, which increases from 2015 to 2040. Compared to the 2022 base case, the 2022 PADD 3 E-set HOF gasolines contain more alkylate and less reformate. In 2040, the PADD 3 E-set HOF gasolines tend to have more FCC and less reformate than the 2040 base case gasoline. The 2022 CA E-set HOF gasolines tend to have more alkylate and naphtha than the 2022 CA base gasoline. In 2040, with the transition to 100% HOF for gasoline market, there is less need for reformate in the CA fuels containing higher amounts of ethanol.

10. For the CRK, LtCOK, and HvyCOK configuration refineries, the 2022 E-set HOF gasolines are dominated by FCC blendstock, while the COKHCK HOFs have more alkylate and less FCC blendstock. In 2040, the CRK, LtCOK, and HvyCOK HOFs have more reformate and less FCC than those in 2022.

11. For 2022 and 2040, the PADD 3 BR-set HOF gasolines are dominated by alkylate and reformate, just as in the 2022 and 2040 base cases.

Gasoline BOB WTP Results (Section 7)

12. For each E set gasoline BOB produced in an aggregate (regional) refinery, the WTP GHG emissions increase in the order of PADD 3 < CA < PADD 2. The highest GHG emissions occur for gasoline produced in a PADD 2 refinery. Those are attributed to the use of energy-intensive oil sands, which consume significant amount of fossil energy (especially natural gas) during recovery and processing. The high GHG emissions for gasoline produced in a CA refinery is attributed to high natural gas use, mostly for hydrogen production.

    In 2022, for a given gasoline set, the WTP GHG emissions of regular gasoline, compared with HOF gasoline, are different for each fuel (E set or BR set). They can be higher or lower than baseline GHG emissions. The difference in GHGs between the combined domestic gasoline pools and baseline are less pronounced.

    In PADD 3, WTP GHG emissions for E set gasoline BOB increase from 2022 to 2040, caused by a slight increase in the fuel production stage due to crude slate change. In CA, the WTP GHG emissions of E set gasoline BOB decrease, due to less energy use in the fuel production stage; the decrease stems from a decrease in crude input.

    In 2040, for both PADD 3 and CA, Fuel 15 shows the lowest per-MJ GHG emissions for gasoline BOB production compared with other E set fuels and with the baseline, implying that refineries can produce F15 BOB, with large octane contribution from 30% ethanol blending to F15 fuel's mid octane demand of 97 RON. In contrast, of the feasible solutions, the BOBs for the 10% and 20% ethanol blended fuels, F14, F18 and F20, have the highest per-MJ GHG emissions. This is correlated to their various refinery component shares and resultant from various energy inputs (e.g., crude, butane, natural gas, etc.) for these gasoline BOB production, governed by LP modeling to maximize profits.

13. For each E set domestic gasoline pool's BOB production in a configuration refinery, the WTP GHG emissions increase in the order of CRK <LtCOK < COKHCK < HvyCOK. The increase in GHG emissions comes from both the feedstock stage (crude recovery) and fuel production stage (refinery process). For the former, the heavier crude used in more complex refineries consumes more energy; for the latter, more hydrogen is needed in a more complex refinery, resulting in more natural gas consumption. It is worth noting that with increasing refinery complexity, more HOF cases show higher GHG emissions than baselines.

14. In 2022, all BR set domestic gasoline BOBs in PADD 2 and PADD 3 show less total energy use than baselines, owing to the high octane numbers the BR stream provides. From 2022 to 2040, for both BR2 and BR4-T BOB production, GHG emissions in PADD 2 decrease while those in PADD 3 increase slightly.

15. For configuration refineries, BR2 gasoline BOBs have lower GHG emissions than baselines for three configuration refineries (CRK, LtCOK, and HvyCOK). With higher GHG emissions than BR2 BOBs, BR4-T gasoline BOBs show slightly higher GHG emissions than baseline in the HvyCOK refinery.

16. When aggregate refineries are compared to configuration refineries, some observations are made below.

    A given fuel's (E set or BR set) WTP GHG missions in PADD 3 refinery are between those of the LtCOK and HvyCOK refineries. This is an expected result, as a PADD 3 refinery is a conceptual aggregate refinery summing up all PADD 3 refineries physically present nowadays, which are predominantly LtCOK and HvyCOK refineries.

    Comparing the WTP GHG emissions for E set fuels in a CA refinery with those in a COKHCK refinery shows that emissions in the former are slightly higher, with the difference stemming from the feedstock stage (crude recovery). The GHG emissions at the fuel production stage (refinery processing) are similar for the two refineries. This is consistent with the general observation that refineries in CA are predominantly the COKHCK type.

17. WTP GHG emissions for BR set gasoline BOB and E set gasoline BOB were compared for a PADD 3 refinery and for CRK, LtCOK, and HvyCOK refineries.

    In a PADD 3 refinery, with the same RON at 97 and similar bio-blending levels, the BR2 BOB (to blend with 27 vol% BR) has higher WTP GHG emissions than the Fuel 15 BOB (to blend with 30 vol% ethanol). Interestingly, the former has slightly lower energy intensity than the latter during refinery processing. However, the different energy sources (crude, natural gas, electricity, heavy oil, butane, etc.) carry different energy and GHG burdens during the recovery and transportation stages. Thus, the higher WTP GHG emissions of BR2 in PADD 3 are explained by the more energy-intensive resources that are used in the refining process.

    A comparison of the BOBs for BR4-T and Fuel 19 shows the opposite trend, with the former having lower GHGs and using lower energy input during the refining process. It is worth mentioning that BR4-T uses toluene as a surrogate for BR split, thus it has great advantage of providing high octane number but not hitting T90 specification. Similarly, for the CRK, LtCOK, and HvyCOK refineries, the WTP GHG emissions for the BOBs of BR4-T are slightly lower than the BOBs for F19, due to the slightly lower energy use for the former in the refining processes stage.

WTP Results of Ethanol and Bioreformate Blendstocks from Different Sources and Conversion Technologies (Section 7)

WTP energy use and GHG emissions for ethanol and BR production vary significantly with feedstock source and conversion technology.

18. Corn stover ethanol WTP stage uses much more total energy than corn starch ethanol production (about 300% more), but consumes much less fossil energy (about 30% less). Because of the latter, corn stover ethanol has much lower GHG emissions than corn starch ethanol does. The WTP GHG emissions for corn starch ethanol are in the range of 53–57 g/MJ, decreasing slightly from 2015 to 2022, and from 2022 to 2040. One reason is because corn starch ethanol production consumes electricity, and the electricity mix becomes less GHG-intensive in the United States over time. On the other hand, the WTP GHG emissions of corn stover ethanol is in the range of 16–18 g/MJ and increases slightly during this period of time. This occurs because corn stover ethanol plants produce electricity and receives electricity displacement credit,

which dwindles with the "cleaner" electricity mix over time. Also, the corn stover process uses biomass for energy supply whereas the corn starch process uses fossil energy (mainly natural gas) for process steam and heat requirements.

19. Bioreformate (BR) production demands a large amount of hydrogen, which can be provided by purchase, in-situ production, or gasification production. With these three hydrogen sources, the WTP GHG emissions for BR stream are 64, 35 and 25 g/MJ, respectively. The variation in GHG emissions from year to year is negligible. BR production with purchased hydrogen uses smallest amount of total energy, the largest amount of fossil energy (mainly natural gas for the SMR process) and the lowest amount of petroleum energy. BR production with in-situ hydrogen uses the largest amount of total energy, while production with gasification hydrogen uses the least fossil energy.

Vehicle Fuel Economy Results (Section 8)

20. On road energy use, fuel economy, and GHG emission projections from the U.S.DRIVE engine test and vehicle simulation results obtained at ORNL for three different ON/CR ratios were summarized. Those projections were used for PTW calculations in this study.

    In the ORNL study, engine tests on 91 RON fuels were run at 10.5 CR, and on 97 RON fuels largely at 11.4 CR. Vehicle fuel economy was modeled in Autonomie based on the engine test results. Engine tests of fuels with higher octane numbers (97 and 101 RON) at CR 13 could not be completed. The engine efficiency gains with the HOFs were evaluated using three sets of fuel economies under ON/CR ratios of 3.0, 3.7 and 5.6. The ON/CR of 3.0 involves the greatest fuel economy gain. Vehicle "window sticker" fuel economy was estimated using the EPA five-cycle model and based on literature.

Finished Gasoline WTW Results (Section 9)

21. For all base case and HOF cases, the GHG emissions of the PTW stage (fuel combustion) dominate the WTW results. The impact of the ON/CR assumption on GHG emissions is minimal.

22. During the PTW stage, the finished gasoline is combusted and the bio-carbon content introduced with bio-blendstock is released as biogenic CO_2, whereas the fossil carbon embedded in gasoline BOB from refinery production is included in the GHG emissions. Accordingly, the key result is that increased bio-carbon presence in the finished gasoline results in WTW GHG reductions.

23. The bio-blendstock type (ethanol or biorefomate) and content have a large impact on WTP stage GHG emissions with their distinctively different production pathways that consumes different amount of energy, but also influences PTW stage GHG emissions due to the bio-blendstock difference in energy content per carbon content. With similar volume blending level, for each MJ of finished gasoline, BR4/BR4-T have higher bio-blendstock energy share than F19 (29.7% vs 22.6%), thus more biogenic CO_2 emissions and less GHG emissions at PTW stage for BR4/BR4-T.

24. For many cases (more so for the E set fuels than for the BR set fuels), the WTP GHG emissions of gasoline BOB are higher than those of baseline. But the magnitude of GHG emissions increase in the WTP stage of the finished gasoline (0–13 g/MJ, including increase from both BOB and from bioblendstock use) are much less than the magnitude of GHG emissions reduction in the PTW stage of the finished HOFs relative to baseline fuels (1–27 g/MJ), which are due to high levels of bio-blending with ethanol or bioreformate that produces only biogenic CO_2 and higher engine efficiency with higher RON fuels

25. For all cases, the GHG emission reductions are in line with fossil energy reductions but differ from petroleum energy reductions. Petroleum energy use dominates the fossil energy use at the PTW stage, but does not dominate at the WTP stage.

26. All WTW energy use (total, fossil and petroleum) was calculated and compared per MJ of fuel used and per mile driven. Generally, with higher bio-blending levels, total energy use increases relative to baseline, while fossil energy use and petroleum energy use decrease. Changes in fossil energy use result in changes in GHG emissions directionally.

27. As was observed for gasoline BOBs, for a given set of HOFs, the WTW GHG emissions are lower for cases using fuels produced in a PADD 3 refinery than for fuels produced in a CA refinery or in a PADD 2 refinery. For configuration refineries, WTW GHG emissions increase in the order of CRK < LtCOK < COKHCK < HvyCOK.

28. Different ethanol sources have up to a difference of 12% in per-mile WTW GHG emissions of the E set HOFs. Corn stover ethanol has lower GHG emissions than corn starch ethanol. Similarly, different sources of hydrogen for production of the BR set HOFs have a difference of up to 16% in WTW GHG emissions. Gasification H_2 has lower GHG emissions that in-situ H_2, which has lower GHG emissions than purchased H_2.

29. For bio-blend HOFs, the ethanol or BR blending level has the most impact on GHG emissions reductions. With 30 vol% ethanol blending, Fuel 15 and Fuel 19 have the greatest WTW GHG emission reductions among the E set fuels. With 27 vol% blending, BR2 and BR4-T have the greatest WTW GHG emission reductions among the BR set fuels.

    In aggregate refineries (PADD 3 and CA only), F15 and F19 with corn stover ethanol reach 9% fleetwide GHG reductions in 2022 and 12%–13% in 2040 on the per-MJ basis. On a per-mile basis, GHG reductions reach 12%–13% in 2022 and 17%–20% in 2040. F19 has greater reductions than F15 owing to its higher RON, which enables more fuel economy gain in engines that can take advantage from higher RON.

    In configuration refineries, for a given HOF, GHG reductions (compared to baselines) are similar for all configurations. On a per-MJ basis, Fuel 19 with corn stover ethanol reduces GHG emissions by 9%–10% in 2022 and by 14%–15% in 2040. On a per-mile basis, F19 with corn stover ethanol reaches GHG emissions reductions of 9%–11% in 2022 and 17%–19% in 2040.

30. For BR set HOFs, the hydrogen source for the BR production process has a significant impact on GHG emissions. The process with purchased hydrogen has the highest fossil energy use, but the lowest total energy use and lowest petroleum energy use. Use of renewable hydrogen, either in-situ hydrogen or gasification hydrogen, reduces GHG emissions significantly. The greatest reduction can be achieved with gasification hydrogen.

    In aggregate refineries (PADD 2 and PADD 3), the differences between BR WTW GHG emissions and baselines are similar among different PADD refineries and for different BR set fuels. On a per-MJ basis, in 2022, BR2 and BR4-T domestic gasolines with BAU gasoline ethanol from corn stover and with BR produced with gasification hydrogen show the greatest GHG emission reductions, reaching 11%–12%. In 2040, with 100% HOF gasoline, BR2 and BR4-T set fuels can reduce WTW GHG emissions by 17%–19 % by using gasification hydrogen, compared with the baseline with corn stover ethanol. On a per-mile basis, the BR set fuels with corn stover ethanol and gasification hydrogen show the greatest GHG reductions: about 13%–14% in 2022 and 19%–24% in 2040.

    In configuration refineries (CRK, LtCOK, and HvyCOK), the differences between BR WTW GHG emissions and baselines are similar among different configuration refineries and for different BR set fuels. On a per-MJ basis, BR2 and BR4-T domestic gasolines with ethanol from corn stover and with BR produced with gasification hydrogen again show the largest GHG emission reductions, reaching 11%–12% in 2022. In 2040, with 100% HOF gasoline, BR2 and BR4-T set fuels can reduce WTW GHG emissions by 17%–19 % by using gasification hydrogen, compared with the E10 baseline with corn stover ethanol. On a per-mile basis, the BR set fuels with corn stover ethanol and gasification hydrogen show the greatest GHG reductions: about 14% in 2022 and 21%–22% in 2040 (compared with corn starch ethanol). On a per-mile basis, the BR set fuels with corn stover ethanol and gasification hydrogen show the largest GHG reductions: about 14% in 2022 and 21%–22% in 2040 (compared with E10 from corn stover ethanol).

31. For a given fuel (E set or BR set domestic gasoline), the greatest GHG reductions are obtained with a high blending level of ethanol from corn stover or BR with gasification H_2. WTW GHG emission reductions compared with baselines are similar in aggregate refineries and configuration refineries. On a per-MJ or per-mile basis, BR2 and BR4-T fuels have greater GHG reductions than F15 and F19 for all refinery models.

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