EFFECTS OF POSSIBLE CHANGES IN CRUDE OIL SLATE ON THE U.S. REFINING SECTOR'S CO_2 EMISSIONS

FINAL REPORT

Prepared for

INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

By

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INTRODUCTION AND EXECUTIVE SUMMARY

The International Council on Clean Transportation (ICCT) retained MathPro Inc. to assess the effects of possible changes in the U.S. refining sector's crude slate and product slate on the sector's energy use and CO_2 emissions. This report is the final work product of the project.

Background

At present, the U.S. refining sector (including merchant production of hydrogen purchased by refiners) accounts for about 3% of total U.S. GHG emissions. Total refinery emissions have remained essentially constant over the past decade or so, during which improvements in refinery energy efficiency have offset the increased intensity of refining operations resulting from changes in crude slate and the imposition of more stringent standards on refined products.

Over the next two decades, the U.S. refining industry will face and respond to changes of historic magnitude in its crude oil and refined product markets, most notably:

- Increased supplies of Canadian heavy, sour crude oils (both conventional heavy crudes and bitumen crudes produced from oil sands);
- Increased supplies of domestic light, sweet crude oils, produced from new mid-continent plays (e.g., Bakken, Eagle Ford);
- New export markets for gasoline and diesel fuel (primarily the latter) produced in U.S. refineries, resulting in the U.S. becoming a substantial net exporter of refined products;
- Reduced domestic demand for refinery-produced gasoline, as a result of the biofuels mandates in the Renewable Fuels Standard, and the new federal CAFE standards; and
- Reduced gasoline/diesel ratio (G/D) in the refined product barrel, as a result of the biofuels mandates in the Renewable Fuels Standard, the new federal CAFE standards, and the export opportunities for diesel fuel.

As the refining sector's new circumstances unfold and the sector responds to these circumstances, significant changes (up or down) could occur in the CO_2 emissions of U.S. refineries.

The prospective evolution of the U.S. refining sector's CO_2 emissions is of continuing interest to policy makers, NGOs, and the refining industry itself. However, prior studies on the subject did not anticipate the changes in crude and product markets now sweeping the refining industry.

Objectives and Scope

This study developed estimates of the U.S. refining sector's prospective energy and CO_2 emissions over a wide range of scenarios, with each scenario denoting a particular combination of a projected crude oil slate and a projected refined product slate for the U.S. refining sector in future years (2025 or, in some cases, 2030).

The analysis employed the same U.S. aggregate refining model and overall methodology as that described in the recent paper by MathPro published in the journal *Environmental Science and Technology*.[1] But the model as used in this study embodied (i) updated data reflecting recent (2011) U.S. refining operations, (ii) new projections of crude oil supply (by type) and refined product demand, (iii) refined product specifications slated to be in effect in 2025 (including the MARPOL sulfur standards for marine diesel fuel), and (iv) a larger and more diverse set of crude oil supply and refined product demand scenarios than in the previous study.

The analysis focused on refinery operations; it does not encompass upstream activities, such as crude oil production, field upgrading of bitumen crudes (e.g., to produce synthetic crude oils), crude oil transport, or production of bio-fuels blended into finished transportation fuels products.

Technical Approach

The study consisted of three primary tasks.

First, we developed a set of eight prospective aggregate U.S. crude oil slates for analysis. The set includes the current U.S. crude slate and seven other (possible future) aggregate crude oil slates spanning a wide range of properties from *Extremely Heavy* (relatively low quality) to *Very Light* (relatively high quality). The average API gravities and sulfur contents of these prospective crude oil slates are shown in **Table ES-1** below.

Table ES-1: Average Properties of the Alternative Crude Oil Slates

Crude Oil Slate	API Gravity	Sulfur (wt%)
Base (2011)	30.5	1.41
Extremely Heavy	24.6	1.49
Very Heavy	26.3	2.04
Heavy	28.2	1.90
Mid-Range North American Expansion	30.0	1.49
North American Import Independence	31.1	1.63
Light	34.2	1.02
Very Light	35.5	0.93

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[1] Hirshfeld, D. S. and Kolb, J. A., *Analysis of Energy Use and CO2 Emissions in the U.S. Refining Sector, With Projections of Heavier Crudes for 2025*; Environmental Science & Technology; **2012**, **467** (7), pp 3697-3704

The set of prospective crude slates constitutes a progression in average crude "quality" from *Extremely Heavy* to *Very Light*. The set of crude slates spans ranges of average API gravity and sulfur content that are substantially larger than the actual changes in these average properties that have occurred in the aggregate U.S. crude oil slate over the past thirty years.

Two of these aggregate crude slates merit further comment:

- The *Extremely Heavy* crude slate denotes the current California crude slate, extended to the U.S. as a whole.[2]

- The *North American Import Independence* crude slate denotes a crude slate comprising no crudes imported from outside North America – due to large increases in Canadian crude oil supply to the U.S. and in U.S. production from tight formations.

Next, we developed a set of five alternative refined product slates, four of which incorporate the new federal fuel economy (CAFE) standards and different volumes of ethanol and bio-diesel production. All of the alternative product slates are based on *AEO2013 Early Release* Reference case forecasts of U.S. demand for refined products, with various adjustments.

The most notable difference between the five alternative product slates is the hydrocarbon-gasoline-to-distillate (G/D) ratio, which ranges from a high of about 1.16 for the current CAFE standard to a low of 0.81. The lower G/D ratios reflect U.S. refined product slates with full implementation of the new federal fuel economy (CAFE) standards and various assumptions regarding biofuel volumes.

The third task, refinery modeling of the various crude oil slate/refined product slate combinations, began with model calibration, to verify that the initial version of the U.S. aggregate refining model represented aggregate, year-round operations of the U.S. refining sector in 2011. (That is, solutions returned by the refinery model with reported data on refining sector operations in 2011 verified that the model adequately represented the U.S. refining sector's aggregate operations in that year.)

After calibration, we re-configured the refining model to incorporate the prospective U.S. crude oil slates and product slates and used the model to analyze a series of *Study* cases. Each *Study* case represented a unique combination of crude oil and product slate. Results returned by the refining model for each crude oil slate/product slate combination include estimates of:

- Refinery energy use, and refinery CO_2 emissions
- Capital investment for new refining process capacity
- Refining process capacity additions and revamps
- Refined product output

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[2] The California refining sector's crude slate classifies as extremely heavy because it contains a significant volume share of very heavy crude oils (API gravity < 20^o) produced in California and consumed only in California refineries. California refineries have been designed to process extremely heavy crude slates. Hence, as California crude production has declined over the years, California refiners have tended to replace the lost domestic volume with imports of heavy, foreign crudes (mainly from South America and the Middle East).

- Average properties of the gasoline and distillate fuel pools

Comparison of refinery energy use and CO_2 emissions returned in the various crude slate/product slate *Study* cases with those returned for the *Base* case (representing the 2011 U.S. crude oil slate) indicated the extent to which changes in the crude oil slate affect the U.S. refining sector's aggregate refinery energy use and CO_2 emissions.

In addition, we analyzed two Sensitivity cases to assess the effects on U.S. refinery CO_2 emissions and energy use of two changes in product slate: (i) a 25% reduction in refinery-produced jet fuel (resulting from a commensurate increase in the volume of bio jet fuel); and (ii) elimination of the production of petroleum coke.

Summary of Key Results

Tables ES-2 and **ES-3** show the effects on refinery CO_2 emissions and energy use of changes in the *crude oil slate*, for one refined product slate incorporating the new CAFE standards (as projected for 2025 in *AEO2013*).

In Table ES-2, the first two columns show, for each crude slate, the estimated percent changes in (i) total annual refinery CO_2 emissions and (ii) refinery CO_2 emissions per barrel of crude, relative to those of the *Base* crude oil slate. The next two columns show, for each crude slate, percent changes in (i) total annual refinery energy use and (ii) refinery energy use per barrel of crude, relative to those of the *Base* crude oil slate.

Table ES-2: Estimated Percent Change in Refinery CO2 Emissions and Energy Use Relative to Base Crude Oil Slate

	CO2 Emissions		Energy Use	
Crude Slate	Annual	Per Bbl of Crude[1]	Annual	Per Bbl of Crude[1]
Base	-	-		-
Extremely Heavy	15%	14%	11%	10%
Very Heavy	11%	9%	8%	6%
Heavy	7%	6%	5%	4%
Mid-Range North American Expansion	1%	1%	1%	1%
North American Import Independence	0%	0%	0%	0%
Light	-9%	-7%	-6%	-4%
Very Light	-10%	-9%	-7%	-5%

1 Crude volume includes purchased gas oils and residuum.

In Table ES-3, the first two columns show, for each crude slate, the estimated values of (i) total annual refinery CO_2 emissions (in million MeT/year) and (ii) the change in total annual refinery CO_2 emissions per barrel of crude relative to the *Base* crude oil slate. The next two columns show, for each crude slate, the estimated values of (i) total annual refinery energy use (in Quads/year) and (ii) the change in total annual refinery energy use, relative to the *Base* crude oil slate.

Table ES-3: Estimated Refinery CO2 Emissions and Energy Use -- Annual Totals and ∆ Relative to Base Crude Oil Slate

	CO2 Emissions (Million MT/year)		Energy Use (Quads/year)	
Crude Slate	**Annual**	**∆ Relative to Base**	**Annual**	**∆ Relative to Base**
Base	233	-	3.26	-
Extremely Heavy	268	35	3.62	0.35
Very Heavy	260	26	3.53	0.27
Heavy	250	17	3.44	0.17
Mid-Range North American Expansion	237	3	3.30	0.04
North American Import Independence	235	1	3.27	0.00
Light	213	-20	3.08	-0.18
Very Light	210	-24	3.04	-0.22

Detailed results for all crude oil slate/refined product slate combinations considered are presented in Section 4 of the report.

Tables ES-2 and ES-3 indicate that:

- The *Extremely Heavy* (California), *Very Heavy*, and *Heavy* crude oil slates all have CO_2 emission and energy use profiles higher than the *Base* crude oil slate.

  Annual CO_2 emissions with these crude slates range from about 7% to 15% higher than those of the *Base* crude oil slate (6% to 14% higher per barrel of crude).

- The *Light* and *Very Light* crude oil slates have CO_2 emission and energy use profiles lower than the *Base* crude oil slate.

  Annual CO_2 emissions with these crude slates are about 9% and 10% lower, respectively, than those of the *Base* crude oil slate (7% and 9% lower per barrel of crude).

- The *Mid Range Expansion* and *North American Import Independence* crude oil slates have CO_2 emission and energy use profiles that are similar to those of the current U.S. crude oil slate.

The indicated differences in refinery CO_2 emissions and energy use reflect differences between crude slates in the composition of refinery fuel and in the production of on-purpose hydrogen.

> Still gas (refinery-produced) and natural gas (purchased) have different carbon/hydrogen ratios, and hence lead to different CO_2 emissions per unit of refinery energy use. On-purpose hydrogen production, which varies from crude slate to crude slate, generates CO_2 emissions unrelated to fuel use.

The estimated compositions and average properties of the gasoline and distillate fuel pools show only minimal variation from crude slate to crude slate. These compositions and properties are determined primarily by the various regulatory and industry standards that transportation fuels must meet, rather than by the properties of the crude oil slate.

Table ES-4 shows the estimated refinery CO_2 emissions associated with the various crude oil slates (for the refined product slate incorporating the new CAFE standards), expressed in terms of two common measures of the carbon intensity of crude oils: metric tons per barrel of crude oil and grams per megajoule of crude oil energy content.

Table ES-4: Estimated Refinery CO2 Emissions of the Crude Oil Slates -- in Terms of Carbon Intensities

Crude Slate	Metric Tons per Barrel	Grams per Megajoule
Base	0.043	7.0
Extremely Heavy	0.049	7.8
Very Heavy	0.047	7.5
Heavy	0.046	7.3
Mid-Range North American Expansion	0.044	7.1
North American Import Independence	0.043	7.0
Light	0.040	6.5
Very Light	0.040	6.5

The estimates in Table ES-4 show the same general trend as those in Tables ES-2 and ES-3; in particular, the carbon intensity measures decrease uniformly as the aggregate crude oil slate becomes lighter (and lower in sulfur content). However, the range of variation in estimated carbon intensity of the crude oil slate is less than the range of variation in estimated refinery CO_2 emissions. The reason is that, for any given refined product slate, per-barrel refinery CO_2 emissions are determined by total refinery CO_2 emissions and the crude oil charge rate (input volume). The crude oil charge rate required to produce the specified product slate decreases uniformly as the aggregate crude slate becomes lighter; the estimated crude oil charge rate for the *Very Light* crude oil slate is about 4½% less than that of the *Extremely Heavy* crude oil slate.

Overview of the Report

The report comprises four sections and an appendix. The four sections deal with:

1. Development of alternative crude oil slates.
2. Development of alternative refined product slates
3. Refinery modeling methodology
4. Results of the analysis, covering both the Study cases and the Sensitivity cases

The appendix presents the results of the sensitivity analysis dealing with the effects of changes in model assumptions regarding the configuration of the refining model used in the study.

The exhibits referred to in the report follow the appendix.

1. DEVELOPMENT OF ALTERNATIVE CRUDE OIL SLATES

We developed a set of eight prospective U.S. crude oil slates for analysis. The set includes the current U.S. crude slate (referred to as *Base*) and seven other (possible future) crude oil slates spanning a range of properties from Extremely Heavy (relatively low quality) to Very Light (relatively high quality).

The average API gravities and sulfur contents of these prospective crude oil slates are shown in **Table 1** below.

Table 1: Average Properties of the Alternative Crude Oil Slates

Crude Oil Slate	API Gravity	Sulfur (wt%)
Base (2011)	30.5	1.41
Extremely Heavy	24.6	1.49
Very Heavy	26.3	2.04
Heavy	28.2	1.90
Mid-Range North American Expansion	30.0	1.49
North American Import Independence	31.1	1.63
Light	34.2	1.02
Very Light	35.5	0.93

1.1 Methodology

We developed the crude oil slates by combining and adjusting recent production forecasts for

- Canadian bitumen (oil sands) crudes (Canadian Association of Petroleum Producers (CAPP) 2012 forecast);
- Domestic light crudes from shale and other unconventional formations (*AEO 2013 Early Release* and industry forecasts); and
- Other domestic crudes from the U.S. Gulf Coast, Alaska, and California (*AEO 2013 Early Release*).

The adjustments that we made to these production forecasts reflect various assumptions regarding imported crudes, dispositions of the bitumen and tight formation crudes, and the total volume of U.S. crude oil use, as discussed further below.

For purposes of this study, we grouped the individual crude oils processed by U.S refineries into crude oil aggregates, differentiated by *source* and *type*.

- *Source* (geographic area)

We grouped the various sources of crude oil into five regional aggregates: U.S. (domestic), Canada, Mexico, other Atlantic Basin (Latin America, Caribbean, and West Africa), and Rest-of-World (ROW).

- *Type* (crude property and/or resource category)

  We grouped *domestic* crudes by origin: tight oil formations (e.g., Bakken, Eagle Ford), Alaska, California, and all other U.S. producing areas.

  We grouped *Canadian* crudes first by whether they are conventional or oil sands crudes, and second by whether they are light/medium or heavy (for conventional crudes) or light synthetic or heavy (for oil sands crudes).

  We grouped *Mexico*, *Atlantic Basin*, and *ROW* crudes by API gravity category (light, medium, heavy).

Exhibit 1[3] shows these crude oil categories and the corresponding aggregate volume and average properties of the crude oils in each category that were processed by U.S. refineries in 2011.

We developed these estimates using data reported on EIA's[4] website – PADD-level data on crude oil throughput and crude oil properties, and company-level data on crude oil import volumes and properties – and estimates developed in previous studies of the average properties of Alaskan and California crude oils.

We used the estimated average properties for each crude oil category shown in Exhibit 1, in combination with various assumptions regarding possible future crude oil supplies to the U.S. refining sector, to develop a set of possible future U.S. crude oil slates, ranging from extremely heavy (as measured by API gravity) to very light.

The overall intent in constructing the alternative crude oil slates was to span a wide range of possible future crude oil slate compositions and average properties, consistent with recent projections of future supplies of U.S. and Canadian crude oils by EIA and CAPP, respectively. The *Extremely Heavy* crude oil slate is not based on these projections, but rather denotes the crude oil slate currently processed by the California refining sector.[5]

Exhibit 2 lists the sourcing assumptions underlying each of the alternative crude oil slates.

The various entries in Exhibit 2 denote the following:

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[3] The exhibits are located at the end of the report.

[4] *EIA* denotes the Energy Information Administration of the U.S. Department of Energy.

[5] This crude slate was intended to support refinery modeling aimed at yielding some insight into the differences in refinery CO_2 emissions between the California and the aggregate U.S. refining sectors.

- *2011* denotes U.S. crude oil supplies in 2011, as reported by EIA.

- *20xx AEO Ref.* denotes EIA's *AEO2013* projections of crude oil volumes for year 20xx (2025 or 2030) in the Reference (Ref.) case.

- *High-end* denotes private sector projections of production from Bakken, Eagle Ford, and other U.S. tight oil shale plays.

- *Extremely heavy* denotes a prospective U.S. crude oil slate having the same composition and average properties as the aggregate crude slate currently run in the California refining sector.

- *2030 CAPP Projection* denotes CAPP's 2012 projection of Canadian crude oil supplies to the U.S. in 2030.

- *Displaced* denotes the complete displacement from the U.S. crude oil slate of the indicated crude type by a corresponding increase in the supply of other crude types

- *Residual* denotes the additional volume of the indicated crude oil needed to achieve the target crude slate volume of 13,750 K b/d.[6]

Exhibit 2 indicates that

- The *Very Heavy* crude oil slate reflects the CAPP forecast of the supply of Canadian oil sands crudes to the U.S. refining sector for 2030. (As **Exhibit 7** shows, this forecast calls for more than a three-fold increase from 2011to 2030 in Canada's exports of oil sands crudes to the U.S.)

  In constructing this crude oil slate, we assumed that all domestic production of light, tight oil is exported[7] and only heavy foreign crudes are imported; that is, all light/medium imports are displaced. Finally, we assumed that production of other domestic crude oils is as forecast in *AEO2013* for 2030 and all such crudes are used domestically.

  The *Very Heavy* crude slate comprises 38% oil sands crudes, 22% imported conventional heavy crudes, and 40% all other crudes (comprising primarily conventional U.S. crudes). This crude slate reflects growth in the production of oil sands crudes and a shift in U.S. imports of conventional crudes toward heavier (presumably lower-priced) crudes.

- The *Heavy* crude oil slate differs from the *Very Heavy* one only in the assumption regarding the disposition of U.S. light, tight oil. For this crude oil slate, domestic production of light,

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[6] In constructing the various crude slates, we used a single aggregate volume of 13,750 K b/d for projected future crude oil use. This estimate is based on crude oil use consistent with projections of U.S. refined product output for 2025 in *AEO2013 Early Release*.

[7] For the purposes of this study, we assumed that export restrictions on domestically produced crude oil are lifted.

tight oil is as projected for 2030 in the *AEO2013* Reference case and all such crude oil is used domestically (displacing all imports of light crude).

- The *Mid-Range North American Expansion* crude oil slate reflects the assumption that only about half of the CAPP-forecast increase in the supply of Canadian oil sands crudes to the U.S. by 2025 occurs. Domestic production of light, tight crude oil and all other crude oil is as projected for 2025 in the *AEO2013* Reference case.

  We assumed that the projected increase in domestic production of light, tight crude oil displaces light imported crudes (other than Mexican crude) on a barrel-for-barrel basis, and that the imports of medium and heavy crudes needed to meet the specified total crude volume are in the same proportions as in 2011.

- The *North American Import Independence* crude oil slate reflects the assumptions that

  - Canadian crude oil production is as forecast by CAPP for 2030, and all Canadian crude oil available to the U.S. is processed by U.S. refineries.

  - U.S. light, tight oil production rises to about 3.4 MM b/d, and about 2.8 MM b/d of this oil is processed by U.S. refineries, with the rest exported.[8]

  - Other domestic crude oil production is as projected for 2030 in the AEO2013 Reference case, with the small residual volume of crude oil supply coming from Mexico.

  The *North American Import Independence* crude slate comprises 20% light, tight crude, 38% oil sands crudes, and 41% all other crudes (mainly conventional crudes produced in the U.S. and in Canada). This crude oil slate reflects growth in domestic production and consumption of both light, tight crudes and oil sands crudes.

- The *Light* crude oil slate reflects the assumptions that

  - Canadian crude oil supply to the U.S. remains as in 2011 (implying that the projected increases in oil sands production do not materialize or that Canada develops export outlets other than the U.S.).

  - Production of domestic light, tight oil increases to about 3.4 MM b/d, and all production of domestic light, tight oil is used in the U.S.

  - Other domestic crude production is as projected for 2025 in the *AEO2013* Reference case.

  We assumed that imports of light and medium crude oil from the Atlantic Basin continue at 2011 volumes (notwithstanding the increase in production of light domestic crudes). The residual crude supply is assumed to be heavy Atlantic Basin crudes.

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[8] See *New Crudes, New Markets*; Platts Special Report; October 2012.

- The *Very Light* crude oil slate reflects the assumptions that
    - Canadian crude oil supply to the U.S remains as in 2011.
    - Production of domestic light, tight crude oil increases to 3.4 MM b/d.
    - Production of all other domestic crudes is as projected for 2030 (rather than 2025) in the *AEO2013* Reference case (resulting in a relatively small increase in domestic crude supply).
    - All imported crude oil is either light or medium (in the same proportions as in 2011), with about 40% imported from the Atlantic Basin and 60% from ROW.

  This latter assumption is the primary difference between this crude slate and the *Light* crude slate.

  The *Very Light* crude oil slate comprises 25% light, tight crudes, 26% imported light and medium crudes, and 49% all other crudes (mainly non-light U.S. conventional crudes and Canadian crudes, in the volumes imported by the U.S. in 2011). This crude oil slate reflects growth in domestic production and consumption of light, tight crudes and in imports of light and medium crudes.

1.2 Composition and Average Properties of the Alternative Crude Slates

Exhibit 3 shows the computed composition of the various aggregate crude oil slates, by crude type, and the average whole crude properties of the resulting aggregate crude oil slates.

Exhibits 4.1 and **4.2** show the estimated distillation curves for each alternative aggregate crude oil slate, along with the estimated distillation curves for the current (2011) U.S. aggregate crude oil slate. Exhibit 4.1 shows the distillation curves for the four heaviest alternative crude oil slates; Exhibit 4.2 shows the distillation curves for the three lightest.

> A *crude distillation curve* is a plot of the cumulative volume percent of a crude oil evaporated as a function of temperature when a crude oil is heated to progressively higher temperatures. The heavier a crude oil, the “lower” its distillation curve on a plot of volume percent evaporated vs. boiling temperature.
>
> Every crude oil is a mixture of thousands of hydrocarbon compounds of different carbon content (ranging from 2 to > 60 carbon atoms) and molecular weight. In general, the more carbon atoms in a hydrocarbon molecule, the heavier and more dense the material and the higher its boiling temperature. As one heats a crude oil to progressively higher temperatures, the various compounds boil off in sequence: first the lightest (lowest carbon number) compounds, followed by progressively heavier compounds as the temperature is increased. This characteristic enables the separation of crude oils into distinct *fractions*, characterized by

their boiling range, in a standard refining process (*crude distillation*) that is the starting point for all other refining processes and operations.

As Table 1 and these exhibits indicate, the average API gravities of the alternative crude oil slates range from about 24.6° to 35.5°; the average sulfur content ranges from about 0.9 wt% to 2.0 wt%.[9]

Exhibits 5, 6.1, 6.2, and 6.3 show aggregate properties of the various crude oil components of the prospective crude slates shown in Exhibits 4.1 and 4.2

Exhibit 5 shows average whole crude properties and distillation curves for the two types of North American crude oils whose production volumes are projected to increase substantially: light, tight oil and crudes produced from Canadian oil sands.

With respect to the light, tight oils, Exhibit 5 shows properties and distillation curves for both Bakken and Eagle Ford crude types. Crudes produced in the Eagle Ford play have API gravities range that from $\approx$ 40° API to > 60° API. The representation of Eagle Ford crude shown in Exhibit 5 is based on a recently published "average" assay.[10]

As Exhibit 5 shows, the tight formation crudes are considerably lighter than the current U.S. composite crude slate. As more of these crudes enter the U.S. crude oil slate, it will become lighter (all else equal).

Exhibits 6.1, 6.2, and 6.3 show average whole crude properties and distillation curves of the primary components, by crude type, of the *Very Heavy*, *North American Import Independence*, and *Very Light* prospective crude slates.

1.3 Additional Comments

The Canadian oil sands crudes are supplied to U.S. markets in the form of either synthetic crude oil (*SCO*) or *dilbit*. SCO is a light, low sulfur crude containing no residual oil material ("vacuum resid"), produced by local upgrading (via coking or thermal cracking) of bitumen. Dilbit is a heavy crude oil material that is a mixture of in-situ-produced bitumen and one or more diluents, such as condensate (the most used), SCO, or conventional crude.

The heavy Canadian oil sands crudes (dilbit and heavy conventional crudes) are considerably heavier than the current U.S. composite crude oil slate, and the volume share of these streams far outweighs the volume share of SCO in Canadian exports to the U.S. Consequently, the volume-weighted average of Canadian oil sands crudes exported to the U.S. is considerably heavier than current U.S. composite crude oil slate (as shown in Exhibit 6.1).

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[9] By contrast, we assessed crude oil slates with API gravity ranging from to 27.1° to 30.6° in our recent paper in *Environmental Science and Technology*.

[10] *The Eagle Ford Marker: Rationale and Methodology*; Platts Methodology and Specifications Guide; October 2012

Most of the variation in the average properties of the various crude oil slates (shown in Exhibit 3) is determined by the specified volume shares of (i) Canadian oil sands crudes; (ii) domestic light, tight oil crudes[11]; and (iii) light/medium or heavy imported crude. (For purposes of this analysis, we varied the volume shares of these crude types from crude oil slate to crude oil slate, but held the average properties of each crude oil type constant at the values shown in Exhibit 1.)

The set of crude oil slates indicates the nature of the relationship between changes in the pattern of crude supply and the consequent changes in the average properties of the aggregate U.S. crude slate. Significant changes in crude oil sourcing are required to move API gravity by four degrees and sulfur content by 0.5 wt%, either higher or lower, relative to the corresponding values for the current crude slate.

The set of prospective crude oil slates spans a broad range of properties, as indicated by the average API gravities and sulfur contents shown in Exhibit 3, to support a robust refinery modeling analysis. Indeed, the set spans ranges of average API gravity and sulfur content that are substantially larger than the actual changes in these average properties that have occurred in the aggregate U.S. crude oil slate over the past thirty years.

The *North American Import Independence* crude slate is an example of what is sometimes called a “dumbbell” crude slate, because it comprises mainly very light crudes (from U.S. tight formations) and very heavy crudes (Canadian bitumens). The term “dumbbell” reflects the assumption that such crude slates consist mainly of light (low-boiling) material and heavy (high-boiling) material, and are deficient in middle-of-the-barrel material (i.e., kerosene and distillate). However, such is not the case. As Exhibit 4.2 indicates, the composite distillation curve for the *North American Import Independence* crude oil slate shows no deficiency in middle-of-the-barrel boiling material. This is because (i) very light crudes still contain significant fractions of mid-range and heavy material, (ii) very heavy crudes still contain significant fractions of light and mid-range material, and (iii) the aggregate crude slate still contains significant fractions of medium weight crudes.

Finally, we developed the possible crude oil slates independent of the possible future U.S. refined product slates (which are discussed in the next section). Subsequent refinery modeling revealed that all the crude oil slates are technically compatible with the range of product slates developed below, in the sense that the product slates can be produced from each crude oil slate with current refining process technology.

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[11] Crude oil assay data available to us indicate that light, tight oil from the Bakken play has average API gravity/sulfur content of about $41.8^o/0.13\%$. Light, tight oil from the Eagle Ford play has API gravity of about 35^o to 65°, depending on the location within the Eagle Ford play. We represent Eagle Ford crude as having an average API gravity/sulfur content of $43.2^o/0.15\%$.

2. DEVELOPMENT OF REFINED PRODUCT SLATES

We developed a set of five alternative refined product slates, across which the hydrocarbon-gasoline-to-distillate (G/D) ratio ranges from slightly below the current level to significantly lower levels. The lower G/D ratios reflect U.S. refined product slates with full implementation of the new federal fuel economy (CAFE) standards and various assumptions regarding biofuel volumes.

Exhibit 8 lists alternative refined product slates, along with the assumptions we used in constructing them. The layout and terminology in Exhibit 8 are similar to those in Exhibit 2. (The term *MARPOL* denotes the MARPOL Annex VI sulfur standards for fuels powering marine diesel engines, promulgated by the International Maritime Organization.)

Exhibit 9 shows the composition of each alternative product slate, along with the corresponding G/D ratio. The G/D ratios vary from a high of about 1.16 to a low of 0.81 for the 2035 product slate. The 2035 product slate reflects high ethanol use, low bio-diesel production, and full implementation of the newly promulgated CAFE standards.

All of the alternative product slates shown in Exhibit 9 are based on *AEO2013* Reference case forecasts of U.S. demand for refined products, with various adjustments.

- The *Current CAFE Standards* product slate incorporates an upward adjustment to the *AEO 2013* hydrocarbon gasoline volume to reflect higher gasoline demand resulting from a vehicle fleet with lower fuel economy than assumed in *AEO 2013*.

- All of the other refined product slates reflect demand for hydrocarbon gasoline consistent with the newly promulgated CAFE standards (which are incorporated in *AEO 2013*).

- The residual oil product meets the MARPOL sulfur standards in all product slate scenarios.

- The last three product slates shown in Exhibit 9 reflect the 2011 volumes of bio-diesel and other non-refinery liquids blended into the distillate pool. (*AEO 2013* forecasts a significant increase in the volumes of non-refinery blendstocks for distillate fuels, but not as much as *AEO 2012* forecast.)

- The last two product slates shown in Exhibit 9 reflect the phase-in of 30% ethanol blending in the gasoline pool, with E30 constituting about 50% and 100%, respectively, of the gasoline pool in 2025 and 2035. (The use of high-octane E30 blends in conjunction with advanced engine designs is among the options for meeting the new CAFE standards being considered by vehicle manufacturers.)

The new CAFE standards, reduced production (relative to the AEO2013 Reference case) of bio-diesel and other "non-petroleum-based" distillate blendstocks, and higher levels of ethanol blending all work to reduce hydrocarbon gasoline demand and increase hydrocarbon distillate demand. The elements enter the product slates so as to progressively lower the G/D ratio across the alternative product slates. Consequently, all of the prospective product slates have G/D ratios lower than that of the actual 2011 product slate.

Finally, we developed two secondary product slates as variants of the New CAFE Standards product slate, for use in the two sensitivity cases described in Section 5. One of the secondary product slates embodies a 25% reduction in the refinery output of hydrocarbon jet fuel, to reflect use of a like volume of bio-jet. The other secondary product slate reflects zero production of petroleum coke in the U.S. refining sector.

3. REFINERY MODELING METHODOLOGY

We employed linear programming (LP) modeling to assess the effects of changing crude and product slates on the operations of the U.S. refining sector and on U.S. refinery energy use and CO_2 emissions.

Discussions of the application of refinery LP modeling in general and MathPro's refinery modeling methodology in particular are presented in two recent publications, to which we refer the interested reader:

- Hirshfeld, D. S. and Kolb, J. A., *Analysis of Energy Use and CO_2 Emissions in the U.S. Refining Sector, With Projections of Heavier Crudes for 2025*; Environmental Science & Technology; **2012**, **467** (7), pp 3697-3704; DOI: 10.1021/es204411c [12]

- *Technical and Economic Analysis of the Transition to Ultra-Low Sulfur Fuels in Brazil, China, India, and Mexico*; prepared for ICCT by Hart Energy and MathPro Inc.; October 2012; http://www.theicct.org/technical-and-economic-analysis-transition-ultra-low-sulfur-fuels-brazil-china-india-and-mexico.[13]

The first reference includes a discussion of the methodology incorporated in the refining model to estimate refinery energy use and, from that, refinery CO_2 emissions.

Following are brief comments on some key aspects of the refinery modeling methodology employed in this study.

3.1 Model Calibration

In keeping with our standard methodology, we first calibrated our U.S. aggregate refining model to represent aggregate, year-round operations of the U.S. refining sector in 2011.

- The 2011 refinery crude oil slate input to the model was developed using company-level crude oil import data, state and offshore crude oil production data, and PADD-level crude oil property data reported by EIA.

- Annual refinery input and output volumes were based on corresponding data for 2011 reported by the EIA.

- Aggregate U.S. refining capacity was developed using the 2011 *Oil & Gas Journal* survey of refining capacity, supplemented with information on refining process capacity reported by EIA.

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[12] In particular, see Section 6 of the Supporting Information document that accompanies the paper.

[13] Sections 3 and 4 of the report address refinery modeling methodology.

We compared the solutions for 2011 returned by the aggregate refining model with the reported data on refining sector operations (described above) and verified that the model adequately represented the U.S. refining sector's aggregate operations in 2011. We adjusted refinery energy use, by form (natural gas, still gas, etc.), such that values returned by the model closely agreed with those reported by EIA for the U.S. refining sector in 2011.

Table 2 shows results of the 2011 calibration, along with reported information on key measures of refining operations. With the exception of shadow values and prices for distillates, the calibration results are reasonably close to reported information.

We adjusted refinery fuel and power use in the calibrated refinery model so that model output closely matched information on refinery energy use reported by EIA for 2011.

3.2 Study Cases Representing Crude Oil Slate/Product Slate Combinations

Following calibration, we re-configured the refining model to incorporate the various crude oil slates and product slates described in Sections 1 and 2, respectively. We specified key properties of the refined products to represent all relevant quality standards on refined products in effect now or scheduled to take effect before 2025. We allowed the refining model to add or revamp refining process capacity (e.g., coking, hydrocracking, etc.) as needed to process each specified crude oil slate at minimum total cost (including capital charges associated with the capacity additions), while maintaining refined product outputs at the volumes specified in each product slate scenario.

Results returned by the refining model for each crude slate/product slate combination include estimates of

- Refinery energy use, and refinery CO_2 emissions
- Capital investment for new refining process capacity
- Refining process capacity additions and revamps
- Refined product yield patterns
- Average composition and properties of the gasoline and distillate fuel pools

Comparison of refinery energy use and CO_2 emissions returned in the various crude slate/product slate *Study* cases with those returned for the *Base* case (representing the 2011 U.S. crude oil slate) indicate the extent to which changes in the crude oil slate affect the U.S. refining sector's aggregate refinery energy use and CO_2 emissions.

Table 2: Selected 2011 Calibration Results and Reported Information

	Reported	Calibration
Crude Oil Input (K b/d)	14,833	14,712
Operations		
Charge Rates (K/b/d)		
Reforming	2,583	2,723
Fluid Cat Cracking	4,930	4,769
Hydrocracking	1,462	1,340
Coking	2,089	2,109
Operating Indices		
FCC Conversion		70.5
Reformer Severity		95.4
Coke Make (K b/d)		
Marketable	614	590
Catalyst	228	232
Prices/Marginal Cost[1] ($/b)		
Gasoline		
RBOB		111.87
CBOB		110.54
Conventional	115.42	112.14
Distillates		
Jet Fuel	125.92	115.27
Tier 2 Diesel	124.82	115.27
Pool BOB Properties[2]		
RVP (psi)	9.7	9.7
Oxygen (wt%)		0.0
Aromatics (vol%)	23.8	21.4
Benzene (vol%)	0.89	0.63
Olefins (vol%)	8.9	8.7
Sulfur (ppm)	30	23
E200 (vol% off)	47.1	47.5
E300 (vol% off)	82.8	82.7
Energy Use (Billion btu/d)[3]		
Fuel (incl. cat coke)	7,708	7,733
Power[4]	1,715	1,716
Per Barrel of Crude (MM btu/b)[5]	0.61	0.61

1 Gulf Coast spot prices.

2 Reported pool gasoline properties are based on Alliance Gasoline Surveys.

3 Refinery fuel use and pow er consumption are adjusted to closely match estimate developed using reported data.

4 Btu's in delivered pow er, adjusted for generation efficiency and transmission loss

5 Includes purchased gas oils and residuum.

3.3 Sensitivity Cases

In addition to the Study cases, we analyzed two sets of Sensitivity cases, involving additional refinery modeling runs.

3.3.1 Sensitivity of Results to Technical Assumptions

The first set of Sensitivity cases, analyzed prior to the Study cases, assessed the sensitivity of the results returned by the refining model to changes in modeling assumptions regarding (i) the temperature cut point for distillate boiling range material[14] and (ii) the fraction of FCC feed that is hydrotreated prior to FCC processing. We developed these cases to explore some technical issues that arose in the course of configuring the refining model.

The rationale for and results of this sensitivity analysis are presented in the **Appendix**.

3.3.2 Sensitivity Cases Addressing Product Slate Changes

The second set of Sensitivity cases, analyzed after the Study cases, assessed the effects on U.S. refinery CO_2 emissions and energy use of two changes in product slate: (i) a 25% reduction in refinery produced jet fuel (resulting from a commensurate increase in the volume of bio jet fuel); and (ii) elimination of the production of petroleum coke.

We developed these Sensitivity cases by modifying the *New CAFE Standards* product slate (only).

Increasing Bio Jet Fuel Volume (Reducing Refinery Production of Jet Fuel)

The jet fuel case involved simply reducing the refinery output of (hydrocarbon) jet fuel by 25% in the *New CAFE Standards* product slate, to compensate for the potential increase in bio jet fuel (noted above), and re-solving the model.

Eliminating Refinery Production of Petroleum Coke

The petroleum coke case is more complicated and calls for some discussion. This sensitivity case posits that the production of marketable petroleum coke[15] is prohibited by some future regulation, so that the U.S refining sector must change the way that it processes vacuum resid, the heaviest crude oil fraction and the source of petroleum coke.

Marketable petroleum coke ("petcoke") is produced as a by-product by refinery process units called *cokers*. These units convert ("crack") vacuum resid into the lighter, more valuable

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[14] Increasing the distillate cut point increases the flow of material to distillate hydrotreating, but reduces the flow of material to the more energy intensive processes of hydrocracking and cat cracking.

[15] Not FCC catalyst coke, which is used as refinery fuel.

streams that become components of transportation fuels and other valuable products. These lighter streams are less carbon-rich than the coker feeds.[16] The coking process rejects the "excess" carbon in its feed streams in the form of petcoke (which is ≈ 95% carbon). The petcoke is recovered and sold for various low-value end-uses, mostly as low-grade fuel.

Currently, the U.S. refining sector processes nearly all of its vacuum resid in cokers.[17] In recent years, Midwestern refineries in particular have increased coking capacity to accommodate the influx of heavy, Canadian oil sands crudes.

In 2011, the U.S. refining sector produced about 614 K barrels/day of petcoke. Our refinery modeling indicated (Exhibit 11) that refinery production of petcoke associated with the *New CAFE Standards* product slate would vary from about 300 K barrels/day (for the *Very Light* crude oil slate) to over 1000 K barrels/day (for the *Very Heavy* crude oil slate).

To eliminate production of petcoke, U.S. refineries would have to replace their existing coking capacity with new capacity in some other process that would convert essentially all vacuum resid into lighter streams without producing petcoke as a by-product. Such a processing route exists: vacuum resid hydrocracking (VRHC). VRHC converts vacuum resid into lighter streams via hydrogen addition, rather than carbon rejection. Several licensed VRHC processes are in commercial operation in refineries world-wide (though not in the U.S.). According to available trade literature, the most advanced of these processes are capable of processing a wide range of vacuum resids, including vacuum resids from Canadian oil sands crudes, at extremely high conversion rates (> 95%).[18] However, commercial experience at conversion levels this high – especially with vacuum resids from very heavy crude oils – is quite limited.

Because VRHC with extremely high conversion levels is a relatively new process that is not widely practiced, there is more uncertainty and less published data regarding its process yields, product qualities, commercial run lengths, and investment requirements than for coking (which is a well-established, well understood process). In particular, information on the economics of introducing VRHC processes into existing refineries (to displace existing cokers) is sparse, but it is likely that building a VRGC unit to replace an existing coker (as the sensitivity case denotes) would be more costly than building such a unit on a grass-roots basis.

By its nature, VRHC likely would be one of, if not the most, expensive refining process in terms of investment dollars per barrel of throughput. However, VRHC offers one significant advantage over coking; namely, that VRHC yields much larger volumes of lighter, high-value

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[16] Cokers also process certain heavy refinery-produced streams, such as FCC clarified oil.

[17] A relatively small volume of vacuum resid is processed by some U.S. refineries in solvent deasphalters and in resid fluid cat crackers.

[18] Two such processes are *LC-Fining*™ and *Uniflex*™. LC-Fining™, which uses an "ebullated" catalyst bed, appears to be best suited for converting light and medium vacuum resids. Uniflex™, which uses a slurry process with an entrained catalyst, appears to be capable of converting heavy, high sulfur vacuum resids, such as those in Canadian oil sands crudes.

refinery streams. In certain circumstances, this yield benefit might be sufficient to justify a VRGC unit on economic considerations, despite the extremely high investment requirement.

To conduct this sensitivity analysis, we incorporated into the refinery model a new representation of VRHC process technology, based on the limited information available from the trade literature and some supplemental information provided by knowledgeable contacts from the refining sector. The representation reflects the assumption that the VRHC technology could achieve > 95% conversion of vacuum resid – that is, essentially eliminating refinery production of petcoke – for all vacuum resids, even those from the heaviest crude oil slates.

The sensitivity analysis spanned all of the crude oil slates, with the *New CAFE Standards* product slate (only). The refinery model runs for the sensitivity cases involved disallowing the production of petcoke and allowing investment in new VRHC capacity, as well as in the additional capacity required in supporting processes (e.g., sulfur recovery, hydrogen production, etc.).

4. RESULTS OF THE ANALYSIS

This section presents the results of the refinery modeling for the complete set of crude oil and product slates.

- First, we present an extensive set of results, for all crude oil slates, for *AEO2013's* Reference case product slate projection for 2025 – the *New CAFE Standards* product slate – including, refining process capacity additions and utilization, refining operations, refinery inputs and output volumes, refined product properties and composition, refinery CO_2 emissions, and refinery energy use.

  In some sense, the *New CAFE Standards* product slate is probably the one "most likely" to materialize out of the product slates considered in this study. This product slate features refinery outputs of gasoline less than, and of jet and diesel fuel greater than, those in 2011, resulting in a reduced G/D (gasoline/distillate) ratio. Total refined product volume (excluding coke and sulfur) in this product slate is about 4% lower than the actual product volume in 2011. The reduced product volume leads to reduced crude oil throughput (relative to 2011) for all of the crude oil slates considered.

- Next, we present results for refinery CO_2 emissions, refinery energy use, and refinery investments for all crude oil slates and product slates.

- Finally, we present selected results of the sensitivity analyses.

4.1 Results for the New CAFE Standard Product Slate

Table 3 shows the results of primary interest from the refinery modeling of the *New CAFE Standard* product slate: the effects on refinery CO_2 emissions and energy use of changes in the crude oil slate.

The table's first two columns show percent changes in (i) total annual refinery CO_2 emissions and (ii) refinery CO_2 emissions per barrel of crude, relative to those of the *Base* crude oil slate.

The table's next two columns show percent changes in (i) total annual refinery energy use and (ii) refinery energy use per barrel of crude, relative to those of the *Base* crude oil slate.

As Table 3 indicates,

- The *Mid Range Expansion* and *North American Import Independence* crude oil slates have CO_2 emission and energy use profiles that are similar to those of the current U.S. crude oil slate.

Table 3: Estimated Percent Change in Refinery CO2 Emissions and Energy Use Relative to Base Crude Oil Slate

	CO2 Emissions		Energy Use	
Crude Slate	Annual	Per Bbl of Crude[1]	Annual	Per Bbl of Crude[1]
Base	-	-		-
Extremely Heavy	15%	14%	11%	10%
Very Heavy	11%	9%	8%	6%
Heavy	7%	6%	5%	4%
Mid-Range North American Expansion	1%	1%	1%	1%
North American Import Independence	0%	0%	0%	0%
Light	-9%	-7%	-6%	-4%
Very Light	-10%	-9%	-7%	-5%

[1] Crude volume includes purchased gas oils and residuum.

- The *Extremely Heavy*, *Very Heavy*, and *Heavy* crude oil slates all have CO_2 emission and energy use profiles higher than the *Base* crude oil slate.

  Annual CO_2 emissions with these crude slates range from about 7% to 15% higher than those of the *Base* crude oil slate (6% to 14% higher per barrel of crude). Energy use per barrel of crude ranges from about 4% to 10% higher than with the *Base* crude oil slate.

- The *Light* and *Very Light* crude oil slates have CO_2 emission and energy use profiles lower than the *Base* crude oil slate.

  Annual CO_2 emissions with these crude slates are about 9% and 10% lower, respectively, than those of the *Base* crude oil slate (7% and 9% lower per barrel of crude). Energy use per barrel of crude is about 4% and 5% lower than with the *Base* crude oil slate.

The differences between the percentage changes in refinery CO_2 emissions and in refinery energy use reflect differences between crude slates in the composition of refinery fuel and in the production of on-purpose hydrogen.

> The main components of refinery fuel are natural gas (purchased), still gas (refinery-produced), and catalyst coke (refinery-produced). Natural gas and still gas have different carbon/hydrogen ratios, and hence lead to different CO2 emissions per unit of refinery energy use. On-purpose hydrogen production, which varies from crude slate to crude slate, generates CO_2 emissions unrelated to fuel use.

Exhibits 10a, 10b, 10c, and 10d, respectively, show in graphical form for each crude oil slate: (a) total annual CO_2 emissions; (b) CO_2 emissions per barrel of crude; (c) annual energy use; and (d) energy use per barrel of crude. In each exhibit, the left-most bar denotes the *Base* crude oil slate and actual refined product volumes in 2011.

Exhibit 10a, for example, indicates that the product slate projected in *AEO2013* leads to similar or lower annual CO_2 emissions, relative to 2011, for all but the *Extremely Heavy* and *Very Heavy* crude oil slates.

Exhibits 11 and 12 provide more detailed results from the refinery modeling.

- Exhibit 11 provides results bearing on refinery inputs and outputs, fuel use, energy use, and CO_2 emissions, as well as estimates of the carbon intensities of the various crude oil slates.

  As Exhibit 11 indicates, the analysis fixed the volumes of refinery inputs other than crude oil – natural gas liquids, naphthas, gasoline blendstocks, heavy gas oils, and residuum – at values projected for 2025 in *AEO2013*. We allowed the model to vary input volumes of crude oil and butanes in response to changes in crude oil slate and in refining operations. We set minimums on butane input volumes to prevent the model from returning large reductions in purchased volumes for some crude slates.

  The analysis held constant the volumes of most refined products – aromatics, naphthas, aviation gas, hydrocarbon (non-oxygenated) gasoline, jet fuel, diesel fuel, residual fuel, asphalt, and other liquid products – across the various crude slate cases. The model was allowed to vary the volumes of light gases, petroleum coke, and sulfur; consequently, these volumes differ from crude slate to crude slate. Consistent with *AEO2013* projections for 2025, hydrocarbon gasoline (and resid and asphalt) out-turns decline from current levels, jet fuel and diesel fuel out-turns increase, and total refinery out-turns decline by about 4%.

  Light gas, coke, and sulfur out-turns vary with crude slate. More specifically, coke and sulfur out-turns are significantly higher for the *Extremely Heavy*, *Very Heavy*, and *Heavy* crude oil slates than for the *Base* crude oil slate – respectively, 53%, 67%, and 41% more coke and 18%, 49%, and 36% more sulfur. The reverse is true for the *Light* and *Very Light* crude oil slates.

  The volumes of purchased energy (natural gas and electricity), refinery fuel use, total energy use (the sum of fuel use and purchased electricity), and CO_2 emissions all are outputs of the refinery modeling and vary across crude oil slate cases, reflecting changes in refining operations. The *Extremely Heavy*, *Very Heavy*, and *Heavy* crude oil slates not only have higher fuel use than the *Base* crude oil slate, but also use more refinery fuel (still gas) relative to natural gas. (Still gas has a higher carbon emission factor than natural gas). Additionally, due to their higher sulfur contents, the heavy crude oil slates have higher CO_2 emissions resulting from on-purpose hydrogen production.[19]

  A few comments on the results shown in Exhibit 11 may be of interest.

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[19] Refineries remove sulfur from refinery streams to meet sulfur standards on refined products (such as gasoline and diesel fuel) and limit refinery emissions of SOx. Sulfur removal is accomplished by means of *hydrotreating* processes, which consume hydrogen. The higher the sulfur content of a crude oil, the more on-purpose hydrogen production is required to process the crude.

- For all crude oil slates, the total output volume exceeds the crude oil input volume. This reflects the "volume swell" that is associated with the various conversion processes (coking, FCC, hydrocracking) and the volume of the other refinery inputs (e.g., purchased butanes). In general refinery operations are not in volume balance, but they are (of course) in mass balance.

- The volumes shown in Exhibit 11 do not include volumes of condensate (essentially C_6 and lighter material) that are produced in association with certain crudes from shale formations – most notably in the Bakken and Eagle Ford plays – and are separated for sale prior to reaching the refinery. These condensate volumes are used as petrochemical feedstock and as diluent for Canadian bitumen crudes.

- The line item *Coke* under the *Outputs* heading refers to petcoke produced in cokers. The refining model treats all petcoke as a refinery output. The line item *Catalyst Coke* under the *Fuel Use* heading refers to coke produced in FCC units. The refining model treats all catalyst coke as refinery fuel.

  Catalyst coke is so-named because it deposits on the FCC catalyst as it is formed. The coke is burned off to regenerate the catalyst, and the energy released in that coke burn is recovered and used in the refinery.

- The estimated carbon intensity measures decrease uniformly as the aggregate crude oil slate becomes lighter (and lower in sulfur content). However, the range of variation in estimated carbon intensity of the crude oil slate is less than the range of variation in estimated refinery CO_2 emissions. The reason is that, for any given refined product slate, per-barrel refinery CO_2 emissions are determined by total refinery CO_2 emissions and the crude oil charge rate (input volume). As Exhibit 11 indicates, the crude oil charge rate required to produce the specified product slate decreases uniformly as the aggregate crude slate becomes lighter. In particular, the estimated crude oil charge rate for the *Very Light* crude oil slate is about 4½% less than that of the *Extremely Heavy* crude oil slate.

- The estimated energy densities (gross, or higher, heating value) of the various crude oil slates (at the very bottom of Exhibit 11) were computed using the specific gravities and sulfur contents of the various crude oil slates and a correlation developed by MathPro. The correlation expresses crude oil energy density as a function of crude oil specific gravity and sulfur content. The correlation is based on values of gross heating value, density, and sulfur content from assays of a wide range of crude oils.

- Exhibit 12 provides results bearing on selected refinery process operations, additions of new capacity, and retrofits of in-place refining capacity.

  As Exhibit 12 shows, the modeling results indicate that current, in-place U.S. *atmospheric* crude distillation capacity is more than sufficient for all of the prospective crude slates. (In fact, to maintain a refinery utilization rate of about 87%, we reduced current U.S. atmospheric crude distillation capacity by almost 11% by representing the closure of some smaller, less complex refineries.) However, the refining sector would have to add a significant amount of *vacuum* distillation capacity to process the heavier crude slates.

With regard to the conversion processes (which convert the heaviest crude oil fractions into lighter, higher value refinery streams):

- *Coking* capacity must be added for the *Extremely Heavy*, *Very Heavy*, and *Heavy* crude oil slates, but the in-place *coking* capacity is sufficient for the other, lighter crude oil slates.

- The in-place *FCC* (fluid cat cracking) capacity is sufficient for all of the prospective crude oil slates. However, the modeling results suggest that a significant share of FCC capacity would replace their catalysts with commercially available catalysts that increase yields of distillate (jet fuel and diesel fuel) material at the expense of yields of gasoline material, in response to the lower G/D ratio associated with the projected product slate.

- That same incentive to increase distillate yields in response to lower G/D ratios causes the model to add *hydrocracking* capacity for all crude slates, with the largest additions for the heavy crude slates. Hydrocracking produces more distillate material and less gasoline blendstock per barrel of feed than does FCC. Hence, lower G/D ratios favor hydrocracking over FCC.

  The increase in hydrocracking capacity accounts for part of the indicated increase in on-purpose hydrogen production for the heavy crude slates, as hydrocrackers use more hydrogen, on a per-barrel basis, than any other refining process.

The use of *upgrading* processes differs only slightly across the crude oil slates, except that reforming throughput is higher for the light crude oil slates. These crudes contain relatively more naphtha boiling range material than the heavy crude oil slates, and the lighter naphthas have somewhat lower octane than those of the *Base* crude oil slate (calling for more octane generation via reforming).

On-purpose hydrogen production is significantly higher for the heavy crude oil slates than for the *Base* crude oil slate, a consequence of the higher sulfur content of such crudes and the addition of significant hydrocracking capacity to process those crude oil slates. The reverse holds for the light crude oil slates.

Exhibits 13 and 14 show the estimated average properties and composition of the finished gasoline and distillate pools, respectively, for the various crude oil slates.

In general, gasoline and distillate properties remain fairly constant across the crude oil slates. This result stems in large part from the fact that the refining sector must meet the same product specifications and regulatory standards, regardless of the crude slate.

Gasoline composition also changes relatively little across crude oil slates. The estimated gasoline pool composition for all of the crude oil slates includes 12.6 vol% ethanol, consistent with (i) the RFS2 mandate volume for ethanol use from 2022 onward and (ii) the *AEO 2013* Reference case projection of gasoline volume in 2025. By contrast, the average ethanol content of the gasoline pool in 2011 was 9.4 vol%, as Exhibit 13 indicates. This increase in ethanol content, coupled with the accompanying decrease in the FCC naphtha content, accounts for the ≈ 2% reduction in the estimated energy density of the gasoline pool for all of the crude oil slates (relative to the 2011 gasoline pool).

The estimated composition of the distillate pool shows more variation from crude slate to crude slate than that of the gasoline pool. For example, the shares of hydrocracked jet, hydrocracked distillate, and coker distillate are higher for the heavy crude oil slates than for the lighter crude oil slates, a direct result of the addition of greater hydrocracking capacity and coking capacity to process the heavier crude slates.

The average sulfur content of the distillate product pool reported in Exhibit 14 is the volume-weighted average of the sulfur content of diesel fuel (< 10 ppm at the refinery gate) and of jet fuel (≈ 1200–1500 ppm).

4.2 Key Results for All Crude Slate/Product Slate Combinations

Exhibits 15a, 15b, and 15c show the estimated refinery CO_2 emissions and energy use for all combinations of crude oil slate and refined product slate.

- Exhibit 15a shows, for each crude oil slate/refined product combination, the estimated (i) CO_2 emissions in million metric tons per year and in metric tons per barrel of crude and (ii) refinery energy use in quadrillion Btu’s per year and in millions of Btu’s per barrel of crude.

- Exhibit 15b shows the estimated percent changes in refinery CO_2 emissions and energy use, relative to the *Base* crude oil slate, for each crude oil slate/refined product slate combination. This exhibit highlights the effects on refinery CO_2 emissions and energy use of changes in the crude oil slate.

- Exhibit 15c shows, for each crude oil slate/refined product slate combination, percent changes in CO_2 and energy use, relative to the *New CAFE Standard* product slate with each crude slate. This exhibit highlights the effects on refinery CO_2 emissions and energy use of changes in the refined product slate.

Exhibits 15a and 15b indicate that, as one would expect, refinery CO_2 emissions and energy use decrease as one moves across the crude oil slates from *Extremely Heavy* (California) to *Very Light*, for any given product slate.

Exhibit 15b indicates that the patterns of percent changes – relative to the *Base* crude oil slate – in total annual CO_2 emissions, per barrel CO_2 emissions, total annual energy use, and per barrel energy use for the various crude oil slates are similar over the set of product slates, except for the *Full E30* product slate.

> For the *Full E30* product slate, the lighter crude oil slates show relatively smaller percent changes in annual CO_2 emissions and per barrel CO_2 emissions. This different emission profile results from the refinery model using “excess” propylene and butanes (which have higher carbon intensity than natural gas) as refinery fuel. Had we configured the refinery model to allow sales of such “excess” material (a reasonable alternative), the percent changes in CO_2 emissions for the lighter crude oil slates with the E30 product slate would have more closely approximated those of the other product slates.

Exhibit 15c shows that, relative to the *New CAFE Standards* product slate, the percent changes in CO_2 emissions, per barrel CO_2 emissions and per barrel energy use are slightly higher for the *Current CAFE Standards* product slate, similar for the *Low Biodiesel Volume* product slate, and lower for the *Partial E30* and *Full E30* product slates.

> In general, for any crude oil slate, refinery production of gasoline BOBs is a primary determinant of refinery CO_2 emissions and energy use. Thus, the lower refinery out-turns of gasoline BOBs in the *Partial E30* and *Full E30* product slates reduce CO_2 emissions and energy use for those product slates relative to the *New CAFE Standards* product slate.
>
> Within each product slate, the percent changes in CO_2 emissions and energy use are similar for each crude oil slate, except for the light crude slates with the *Full E30* product slate, because the refinery model assigned “excess” propylene and butane volumes to refinery fuel, as discussed above.

Exhibit 16 shows the crude slate volumes returned by the refinery model and the estimated carbon intensities of the various crude oil slates for all combinations of crude oil slate and refined product slate. (The estimated carbon intensities shown in Table ES-4 of the Executive Summary are those shown in Exhibit for the *New CAFE Standards* product slate.)

Exhibit 16 indicates that the carbon intensity of a given crude oil slate depends not only on the properties of the crude oil slate but also (to a lesser extent) on the G/D ratio of the specified refined product slate. For any given crude oil, carbon intensity decreases with decreasing G/D ratio.

Finally, **Exhibit 17** shows the estimated refinery investments in additional and revamped capacity for each crude oil slate/refinery product slate combination.

The values in the *Base* column are the estimated investments in the U.S. refining sector to produce the indicated product slates in 2025 with the 2011 crude oil slate. These investments reflect the combined effects of changes in total product demand and changes in the make-up of the gasoline and/or diesel fuel pools.

The values in the other columns, the estimated refining investments to produce the indicated product slates in 2025 with the other crude oil slates, reflect the effects of crude slate quality on refinery investment requirements.

4.3 Key Results for the Sensitivity Cases on Product Slate Changes

4.3.1 Reduction in Refinery-Produced Jet Fuel (Increase in Bio Jet Fuel)

The primary results of this sensitivity analysis are shown in the bottom section of Exhibits 15a, 15b, and 15c and Exhibit 16.

Exhibits 15a and 15c show that, relative to the *New CAFE Standards* product slate, reducing the volume of refinery-produced jet fuel reduces *total* refinery CO_2 emissions by 1%–2%, but increases *per-barrel* refinery CO_2 emissions and energy use by 1%–2%.

Total CO_2 emissions decline because the reduction in the volume of refinery-produced jet fuel reduces crude oil use and the associated energy use. *Per-barrel* CO_2 emissions and energy use increase, because the reduction in jet fuel production raises the G/D ratio. Producing a higher proportion of gasoline in the refined product slate requires relatively more energy use (on a per barrel basis).

Exhibit 17 indicates that, relative to either the *Current CAFE Standards* or the *New CAFE Standards* product slates, reducing the refinery production of jet fuel by 25% to accommodate increased bio jet volumes would have negligible effect on refinery investment.

The reduction in investment is small because (i) the change in refinery production of jet fuel amounts to < 3% of the crude oil volume and (ii) jet fuel production involves less intensive upgrading of the component refinery streams than do either gasoline or diesel production.

4.3.2 Elimination of Petcoke Production

Here again, the primary results of this sensitivity analysis are shown in the bottom section of Exhibits 15a, 15b, and 15c and Exhibit 17.

Exhibits 15a and 15c indicate that eliminating petcoke production (while maintaining an otherwise constant product slate) would substantially increase refinery CO_2 emissions and energy use for all crude all slates. The largest increases would be associated with the heavier crude slates; the smallest increases (≈ 12%–14%) with the lighter crude slates.

As discussed in Section 3.3.2, eliminating refinery petcoke production (a by-product of coking) would involve replacing all coking capacity with new vacuum resid hydrocracking (VRHC) capacity. This replacement would substantially increase the refining sector's call for on-purpose hydrogen production – a highly energy intensive process, which produces CO_2 as a by-product.

All hydrocracking operations consume large quantities of hydrogen per barrel of feed; in general, the heavier and more sulfurous the feed, the greater the hydrogen consumption. Hence, VRHC units themselves would be exceptionally large consumers of hydrogen. In addition, the refinery streams produced by VRHC (vacuum gas oil, distillates, naphtha, etc.) would require hydrotreating, primarily for sulfur control, before they could be sent to downstream process units or product blending. The corresponding refinery streams produced by coking also require hydrotreating, but the volumes of cracked streams would be higher with VRHC than with coking. (On the other hand, crude oil throughput volume would decline by about 3%–9%, with the smallest reductions associated with the light crude oil slates and the largest with the heavy crude oil slates if cokers were replaced with VRHC units.)

All crude oil barrels have higher carbon/hydrogen (C/H) mass ratios than the refined product barrel; the heavier the crude, the larger the disparity between crude and product C/H ratios. Refineries must eliminate this disparity in the course of transforming crude oil into refined products. The conversion processes in refineries accomplish this task, by removing carbon (coking and FCC) or by adding hydrogen (hydrocracking). The former produces petcoke; the latter produces additional CO_2 and consumes additional refinery energy.

Exhibit 17 shows ranges of estimated investment requirements for eliminating petcoke production for the various crude oil slates. As one would expect, the largest estimates are associated with the heaviest crude slates (≈ $120–$200 billion); the lowest with the lightest crude slates (≈ $50–$100 billion).

These estimated investment requirements, substantial though they are, may not fully capture all of the costs associated with replacing coking with VRHC. High-conversion VRHC itself likely would be more costly than any other refining process in terms of investment dollars per barrel of throughput. Replacing coking with VRHC would entail additional investments in new capacity for on-purpose hydrogen production, downstream hydrotreating, sulfur recovery, source gas treatment, and various refinery utilities and off-sites. In addition, replacing a coker with a VRHC unit would be a major refinery revamp project, which could entail shutting down the refinery for a significant time. We did not consider the costs associated with such a shut-down.

Exhibit 17 shows ranges for the estimated investment requirements because (i) the open literature contains minimal information on investment requirements for VRHC and (ii) commercial experience with high-conversion VRHC is quite limited, especially for processing vacuum resids from heavy crude oils. We have assumed for purposes of this analysis that high-conversion VRHC is technically feasible for all vacuum resid feedstocks, but this remains to be demonstrated.

APPENDIX

Sensitivity Analysis for the New CAFE Standards Product Slate

We developed two sets of additional refinery modeling runs for the *New CAFE Standards* product slate to assess the sensitivity of results to changes in technical assumptions regarding

- The temperature cut point for distillate boiling range material

  Raising the cut point temperature of the distillate cut increases the volume of material going to distillate hydrotreating units, but correspondingly reduces the volume of material going to more energy intensive conversion processes: hydrocracking and cat cracking.

- The fraction of FCC feed that is hydrotreated

  Increasing the fraction of FCC that is hydrotreated increases FCC yields of valuable light refinery streams, but requires investment in new capacity and incurs additional operating costs.

A.1 Distillate Cut Point

With regard to the distillate cut point, the sensitivity runs revealed that increasing the cut point from its nominal value of 620° F to 650° F reduced estimated refinery CO_2 emissions by less than 1% for all Study cases. The reductions in emissions were greatest for the heavier, higher sulfur crude oil slates. The net result is to slightly narrow the spread in percent changes in CO_2 emissions across the various cases relative to the estimates shown in Table 3 of the report.

Increasing the distillate cut point temperature would increase the required operating severity and hydrogen consumption in the distillate hydrotreating units for all crude slates. However, the required increases would be greatest for the heavier, higher sulfur crudes, and sustaining these increases could be problematic in practice.

Accordingly, we maintained the distillate cut point temperature at 620^{o} F across all of the Study cases.

A.2 FCC Feed Hydrotreating

We estimated that the aggregate U.S. refining sector currently hydrotreats about 47% of FCC feed. The California refining sector, whose current crude oil slate serves as the basis for the *Extremely Heavy* crude slate, hydrotreats 100% of FCC feed.

In the refinery modeling underlying the results presented in Table 3 of the report, we represented this aspect of the refining sector's response to changes in crude slate by varying the fraction of

FCC feed that is hydrotreated across the crude oil slates based on the relative volumes of light and medium crudes comprising the crude slate. The heavier crude slates contained relatively less such crudes; consequently, we required more FCC feed hydrotreating for such crude slates. The opposite was the case for the lighter crude slates.

To test the effects of this approach on estimated CO_2 emissions, we developed an alternative set of refinery model runs in which the fraction of FCC feed hydrotreated was fixed at the baseline level of 47% for all crude oil slates (except for the *Extremely Heavy* crude slate, which represents the California refining center's crude slate, for which the baseline level of FCC feed hydroteating of 100% was maintained).

Table A-1 shows the FCC feed hydrotreating assumptions used in our Study cases, the alternative assumptions in the sensitivity cases, the percent change in CO_2 emissions from changing the extent of FCC feed hydrotreating, and the resultant estimates of annual CO_2 emissions relative to the *Base* crude slate.

Table A-1: Effect of Changing FCC Feed Hydrotreating on Estimated Refinery CO2 Emissions and Energy Use

	% FCC Feed Hydrotreating		CO2 Emissions		Energy Use	
Crude Slate	Primary Analysis	Sensitivity Analysis	Change for Each Crude Slate	Total Relative to Base	Change for Each Crude Slate	Total Relative to Base
Base	47%	-	-	-	-	-
Extremely Heavy	100%	-	-	-	-	-
Very Heavy	80%	47%	-1.3%	10%	-1.7%	6%
Heavy	70%	47%	-1.3%	6%	-1.6%	4%
Mid-Range North American Expansion	55%	47%	-0.5%	1%	-0.6%	1%
North American Import Independence	54%	47%	-0.1%	0%	-0.1%	0%
Light	44%	47%	0.3%	-8%	0.4%	-5%
Very Light	38%	47%	0.0%	-10%	0.0%	-7%

Table A-1 shows that maintaining the fraction of FCC feed hydrotreating across the crude slates somewhat reduced estimated refinery CO_2 emissions and energy use for the heavy crude slates and increased them for the light crude slates, thereby narrowing the range of changes in CO_2 emissions and energy use relative to the Base crude slate.

For example, reducing the percentage of hydrotreated FCC feed from 80% to 47% for the *Very Heavy* crude oil slate *reduced* annual refinery CO_2 emissions and energy use for that crude oil slate by 1.3% and 1.7%, respectively. Annual CO_2 emissions for the *Very Heavy* crude oil slate, with reduced FCC feed hydrotreating (47%), are about 10% higher than CO_2 emissions for the *Base* crude oil slate; whereas, with the higher FCC feed hydrotreating (80%) used in the primary analysis, they are about 11% higher than CO_2 emissions for the *Base* crude oil slate (see Table 3 in the report). Similarly, with reduced FCC hydrotreating (47%), energy use for the *Very Heavy* crude oil slate is about 6% higher than for the *Base* crude oil slate, whereas with the higher FCC feed hydrotreating rate (80%), energy use is about 8% higher.

These changes in the modeling results primarily reflect changes in the throughput and energy use of FCC feed hydrotreaters. Changes in hydrogen use in FCC feed hydrotreating exert a secondary effects on refinery CO_2 emissions; an effect that is offset, in part, by compensating changes in hydrogen use in FCC naphtha hydrotreating and distillate hydrotreating. (The sulfur content of feeds to those units is affected by the extent of FCC hydrotreating.) For the *Very Light* crude oil slate, the refinery model reduced hydrocracker feed throughput, offsetting the increased energy use and hydrogen use of expanded FCC feed hydrotreating.

It is not clear how the U.S. refining sector would react to changing crude slates with respect to FCC feed hydrotreating. We consider it likely that FCC feed hydrotreating would increase from current levels if refiners ran increasingly heavy, higher sulfur crude oil slates. Increased FCC feed hydrotreating for these crude slates would (i) control sulfur and metals (catalyst poisons) content in the FCC feed, resulting in longer catalyst life and slightly improved product yields, and (ii) would reduce SOx emissions from FCC units, thereby facilitating regulatory compliance with refinery SOx emissions. Conversely, U.S. refineries might well reduce the extent of FCC feed hydrotreating if crude oil slates become lighter and lower in sulfur.

Ultimately, we concluded that the results reported in Table 3 for the Study cases, in which we varied FCC feed hydrotreating capacity from crude slate to crude slate, more accurately reflected the refining sector's response to changes in crude slate and hence the CO_2 emissions that would be associated with the alternative crude slates.

Exhibit 1: U.S Crude Oil Supply in 2011: Volumes and Average Properties

Origin and Type of Crude Oil	Volume (K b/d)	API Gravity	Specific Gravity	Sulfur (wt%)
Domestic	**5897**	**35.0**	**0.853**	**0.72%**
Light, Tight Oil	187	47.0	0.793	0.11%
Alaska	945	32.0	0.865	0.90%
California	538	17.1	0.952	1.47%
All Other	4,227	36.9	0.840	0.67%
Canada	**2202**	**26.2**	**0.898**	**2.3%**
Conventional				
Light & Medium	588	36.1	0.844	0.73%
Heavy	292	21.3	0.926	3.18%
Oil Sands				
Light Synthetic	308	33.3	0.859	0.21%
Heavy	1014	20.3	0.932	3.52%
Mexico	**1000**	**24.8**	**0.905**	**2.6%**
Light & Medium	247	37.4	0.838	1.05%
Heavy	753	21.1	0.927	3.38%
Atlantic Basin[1]	**3447**	**26.5**	**0.896**	**1.2%**
Light	975	39.9	0.826	0.15%
Medium	561	30.8	0.872	0.32%
Heavy	1911	19.3	0.939	1.92%
Rest of World	**2261**	**32.6**	**0.862**	**1.8%**
Light	332	39.2	0.829	0.65%
Medium	1866	31.9	0.866	2.09%
Heavy	63	20.1	0.933	2.33%
Total U.S.				
As Represented	**14,807**	**30.5**	**0.873**	**1.41%**
Reported by EIA	**14,806**	**30.7**	**0.872**	**1.40%**

1 Comprises Latin America, Caribbean, and West Africa, but excludes North Sea.

Exhibit 2: Assumptions Underlying Alternative Crude Oil Slates

	Crude Slate Designation							
Crude Type	**2011**	**Extremely Heavy**	**Very Heavy**	**Heavy**	**Mid-Range N. American Expansion**	**N. American Import Independence**	**Light**	**Very Light**
Domestic								
Light, Tight Oil	2011	California Slate	Exported	2030 AEO Ref	2025 AEO Ref.	High-End Proj Less Exports	High-End Proj	High-End Proj
Alaska	2011	California Slate	2030 AEO Ref.	2030 AEO Ref.	2025 AEO Ref.	2030 AEO Ref.	2025 AEO Ref.	2025 AEO Ref.
California	2011	California Slate	2030 AEO Ref.	2030 AEO Ref.	2025 AEO Ref.	2030 AEO Ref.	2025 AEO Ref.	2025 AEO Ref.
All other	2011	California Slate	2030 AEO Ref.	2030 AEO Ref.	2025 AEO Ref.	2030 AEO Ref.	2025 AEO Ref.	2025 AEO Ref.
Imports								
Canada	2011	California Slate	2030 CAPP Projection	2030 CAPP Projection	50% of CAPP-projected growth to 2025	2030 CAPP Projection	2011	2011
Mexico								
Light & Medium	2011	California Slate	Displaced	Displaced	Light/medium share of 2025 AEO Ref.	Displaced	Light share of 2025 AEO Ref.	Light share of 2025 AEO Ref.
Heavy	2011	California Slate	Heavy share of 2030 AEO Ref.	Heavy share of 2030 AEO Ref.	Heavy share of 2025 AEO Ref.	Displaced	Heavy share of 2025 AEO Ref.	Displaced
Atlantic Basin[1]								
Light	2011	California Slate	Displaced	Displaced	2011 Light Imports minus Growth in Domestic Tight Oil	Displaced	2011	2011
Medium	2011	California Slate	Displaced	Displaced	2011 Medium share of Residual	Displaced	2011	2011
Heavy	2011	California Slate	Residual	Residual	2011 Heavy share of Residual	Displaced	Residual	Displaced
Rest of World								
Light	2011	California Slate	Displaced	Displaced	Displaced	Displaced	Displaced	Light share of Residual
Medium	2011	California Slate	Displaced	Displaced	Displaced	Displaced	Displaced	Medium share of Residual
Heavy	2011	California Slate	Displaced	Displaced	Displaced	Displaced	Displaced	Displaced

1 Comprises Latin America, Caribbean, and West Africa, but excludes North Sea.

Note: *CAPP Projection* denotes projections in *Crude Oil, Forecasts, Markets & Pipelines, 2012*, Canadian Association of Petroleum Producers.
AEO denotes projections in the Annual Energy Outlook, 2012, Energy Information Agency.

Exhibit 3: Composition of Alternative Crude Slates, by Crude Type

(K b/d)

	Crude Slate Designation							
Crude Type	**2011**	**Extremely Heavy[1]**	**Very Heavy**	**Heavy**	**Mid-Range N. American Expansion**	**N. American Import Independence**	**Light**	**Very Light**
Total Crude Use	**14,807**	**13,750**	**13,750**	**13,750**	**13,750**	**13,750**	**13,750**	**13,750**
Domestic	**5,897**	**6,987**	**5,092**	**6,224**	**6,735**	**7,882**	**8,506**	**8,506**
Bakken	381			720	894	1,477	1,800	1,800
Eagle Ford	187			412	735	1,313	1,600	1,600
Alaska	564	2,381	384	384	350	384	350	350
California	538	4,606	434	434	462	434	462	462
All Other	4,227		4,273	4,273	4,294	4,273	4,294	4,294
Imports	**8,910**	**6,763**	**8,658**	**7,526**	**7,015**	**5,868**	**5,244**	**5,244**
Canada	**2,202**	**264**	**5,868**	**5,868**	**3,678**	**5,868**	**2,202**	**2,202**
Conventional								
Light & Medium	588	12	355	355	383	355	588	588
Heavy	292	8	254	254	264	254	292	292
Oil Sands								
Light Synthetic	308		745	745	665	745	308	308
Heavy	1,014	243	4,514	4,514	2,367	4,514	1,014	1,014
Mexico	**1,000**		**646**	**646**	**923**	**0**	**923**	**212**
Light & Medium	247				228	0	228	212
Heavy	753		646	646	695	0	695	
Atlantic Basin	**3,447**	**2,983**	**2,144**	**1,012**	**2,415**		**2,119**	**1,535**
Light	975	4			245		975	975
Medium	561	222			492		561	561
Heavy	1,911	2757	2,144	1,012	1,678		584	
Rest of World	**2,261**	**3,517**					**0**	**1,295**
Light	332	1556					0	196
Medium	1,866	1887					0	1,099
Heavy	63	74						
Average Properties of the Crude Slate								
API Gravity	30.5	24.6	26.3	28.2	30.0	31.1	34.2	35.5
Sulfur (wt%)	1.41%	1.49%	2.04%	1.90%	1.49%	1.63%	1.02%	0.93%
Specific Gravity	0.873	0.907	0.897	0.886	0.876	0.870	0.854	0.847

1 Current California crude slate is scaled to projected total national crude use. Light and medium crudes imported from rest-of-world are adjusted so that their API gravity and sulfur content matches the reported averages for crudes imported to California.

2 Includes only Bakken/Williston and Eagle Ford shale oil plays.

Exhibit 4.1: Distillation Curves and Average Whole Crude Properties of Alternative Crude Slates

Crude Fractions and Properties	2011 U.S. Crude Slate	Alternative Crude Slates			
		Extremely Heavy	Very Heavy	Heavy	Mid-Range N.Amer Expan.
WHOLE CRUDE					
API Gravity	30.5	24.6	26.3	28.2	30.0
Sulfur (wt %)	1.41%	1.49%	2.04%	1.90%	1.49%
CRUDE FRACTIONS					
LPGs:					
Ethane	0.001	0.000	0.000	0.000	0.000
Propane	0.003	0.002	0.002	0.002	0.003
Isobutane	0.004	0.003	0.004	0.004	0.004
Butane	0.012	0.009	0.012	0.013	0.012
Naphthas:					
Very Light (C5-160)	0.049	0.034	0.049	0.054	0.052
Light (160-250)	0.075	0.054	0.063	0.070	0.074
Medium (250-325)	0.070	0.055	0.056	0.062	0.068
Heavy (325-375)	0.046	0.035	0.037	0.040	0.043
Middle Distillates:					
Kerosene (375-500)	0.118	0.102	0.099	0.104	0.113
Distillate (500-620)	0.121	0.116	0.115	0.116	0.122
Atmospheric Resid:					
Light gas oil (620-800)	0.163	0.172	0.165	0.164	0.166
Heavy gas oil (800-1050)	0.168	0.199	0.174	0.169	0.166
Resid (1050+)	0.173	0.220	0.224	0.202	0.178
SULFUR (wt%)					
Kerosene (375-500)	0.25%	0.27%	0.35%	0.31%	0.25%
Distillate (500-620)	0.68%	0.79%	0.83%	0.75%	0.63%
Gas Oils (620-1050)	1.49%	1.56%	1.87%	1.77%	1.45%
Resid (1050+)	3.59%	2.86%	4.46%	4.58%	3.89%

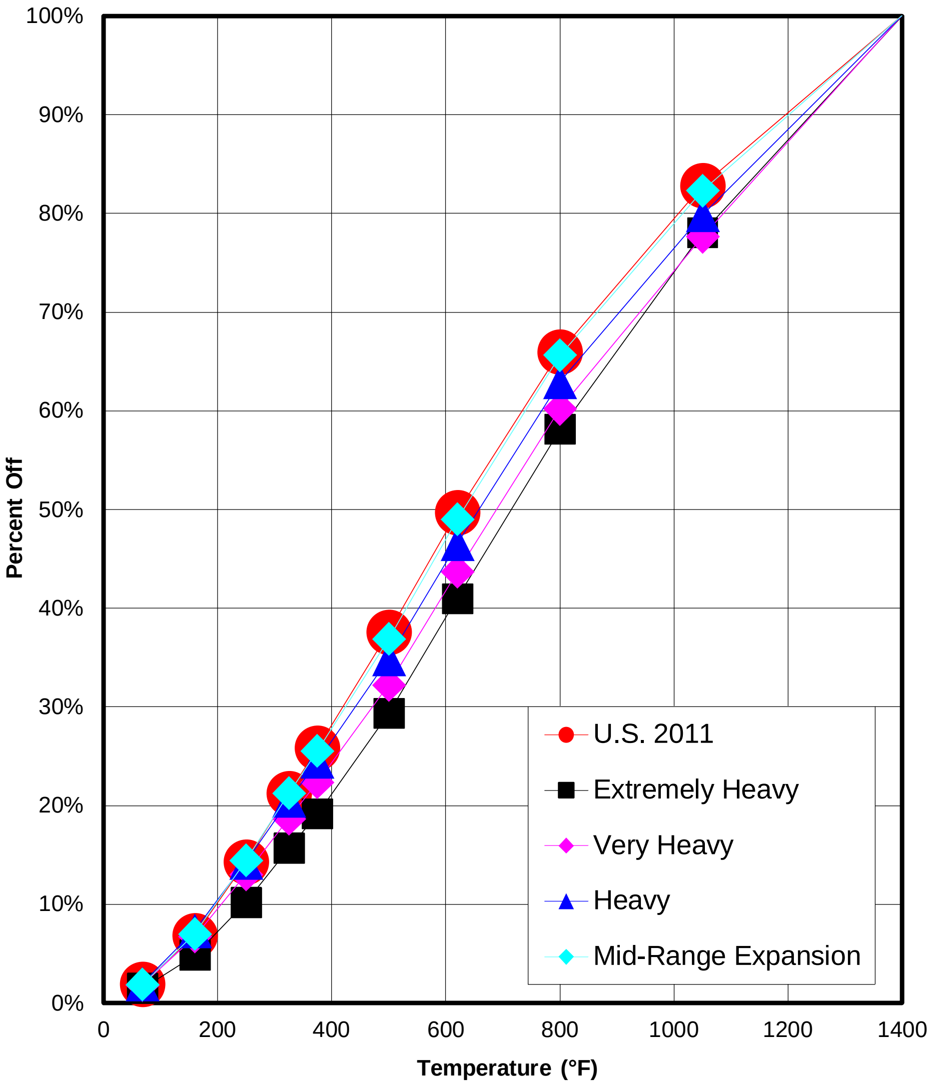


Exhibit 4.2: Distillation Curves and Average Whole Crude Properties of Alternative Crude Slates

Crude Fractions and Properties	2011 U.S. Crude Slate	Alternative Crude Slates		
		N. Amer Import Indep.	Light	Very Light
WHOLE CRUDE				
API Gravity	30.5	31.1	34.2	35.5
Sulfur (wt %)	1.41%	1.63%	1.02%	0.93%
CRUDE FRACTIONS				
LPGs:				
Ethane	0.001	0.000	0.000	0.001
Propane	0.003	0.003	0.003	0.004
Isobutane	0.004	0.005	0.004	0.004
Butane	0.012	0.014	0.012	0.013
Naphthas:				
Very Light (C5-160)	0.049	0.061	0.058	0.061
Light (160-250)	0.075	0.078	0.087	0.090
Medium (250-325)	0.070	0.071	0.081	0.084
Heavy (325-375)	0.046	0.044	0.050	0.052
Middle Distillates:				
Kerosene (375-500)	0.118	0.111	0.127	0.130
Distillate (500-620)	0.121	0.120	0.125	0.127
Atmospheric Resid:				
Light gas oil (620-800)	0.163	0.164	0.162	0.162
Heavy gas oil (800-1050)	0.168	0.163	0.157	0.156
Resid (1050+)	0.173	0.169	0.133	0.117
SULFUR (wt%)				
Kerosene (375-500)	0.25%	0.23%	0.19%	0.16%
Distillate (500-620)	0.68%	0.60%	0.47%	0.44%
Gas Oils (620-1050)	1.49%	1.56%	1.09%	1.08%
Resid (1050+)	3.59%	4.59%	3.32%	3.21%

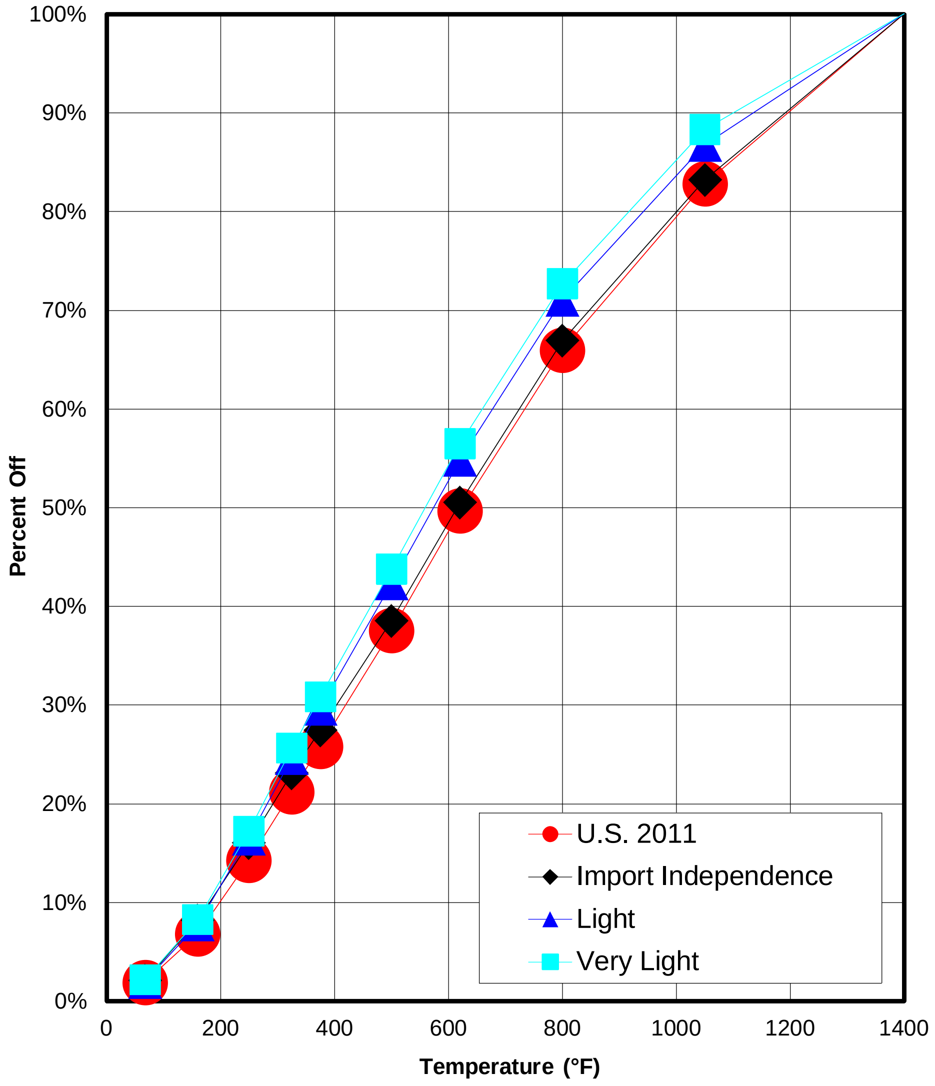


Exhibit 5: Distillation Curves and Whole Crude Properties for Light Tight Oil and Canadian Oil Sands Crudes

Crude Fractions and Properties	2011 U.S. Crude Slate	Light Tight Oil Bakken	Light Tight Oil Eagle Ford	Canadian Oil Sands Syn-thetic	Canadian Oil Sands Heavy
WHOLE CRUDE					
API Gravity	30.5	41.8	47.0	33.3	20.3
Sulfur (wt %)	1.41%	0.13%	0.11%	0.21%	3.52%
CRUDE FRACTIONS					
LPGs:					
Ethane	0.001	0.000	0.000	0.000	0.000
Propane	0.003	0.005	0.002	0.001	0.001
Isobutane	0.004	0.007	0.003	0.004	0.005
Butane	0.012	0.016	0.007	0.017	0.014
Naphthas:					
Very Light (C5-160)	0.049	0.071	0.095	0.051	0.061
Light (160-250)	0.075	0.107	0.122	0.067	0.046
Medium (250-325)	0.070	0.107	0.118	0.062	0.036
Heavy (325-375)	0.046	0.056	0.064	0.042	0.026
Middle Distillates:					
Kerosene (375-500)	0.118	0.149	0.145	0.117	0.066
Distillate (500-620)	0.121	0.136	0.125	0.203	0.093
Atmospheric Resid:					
Light gas oil (620-800)	0.163	0.161	0.150	0.325	0.144
Heavy gas oil (800-1050)	0.168	0.141	0.125	0.111	0.187
Resid (1050+)	0.173	0.044	0.045		0.321
SULFUR (wt%)					
Kerosene (375-500)	0.25%	0.02%	0.02%	0.06%	0.62%
Distillate (500-620)	0.68%	0.09%	0.07%	0.12%	1.38%
Gas Oils (620-1050)	1.49%	0.24%	0.19%	0.38%	3.03%
Resid (1050+)	3.59%	0.68%	0.60%		5.99%

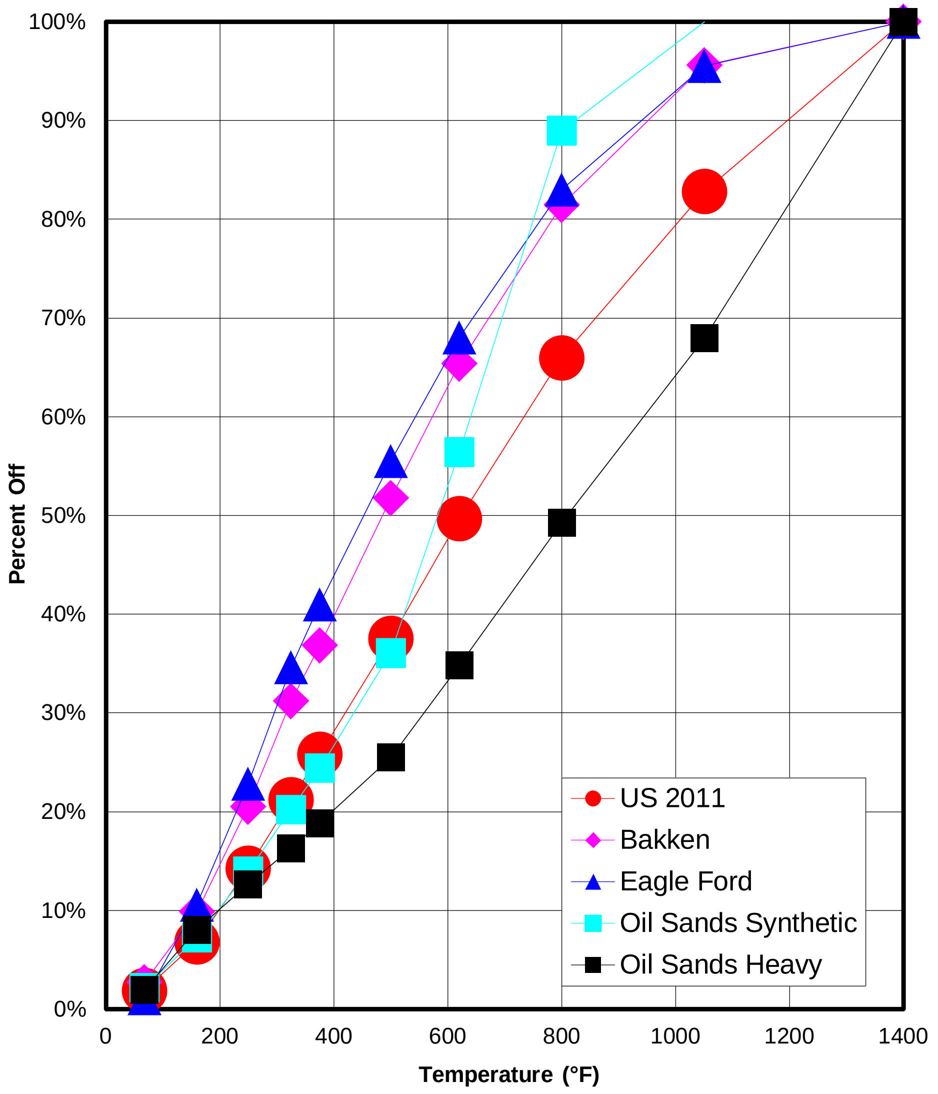


Exhibit 6.1: Distillation Curves and Whole Crude Properties for Components of the Very Heavy Crude Slate

Crude Fractions and Properties	2011 U.S. Crude Slate	Very Heavy Crude Slate	Components		
			Oil Sands Crudes	Imported Conv. Heavy	All Other
WHOLE CRUDE					
API Gravity	30.5	26.3	22.0	19.8	34.7
Sulfur (wt %)	1.41%	2.04%	3.09%	2.33%	0.76%
CRUDE FRACTIONS					
LPGs:					
Ethane	0.001	0.000	0.000	0.000	0.001
Propane	0.003	0.002	0.001	0.001	0.004
Isobutane	0.004	0.004	0.005	0.001	0.004
Butane	0.012	0.012	0.014	0.003	0.014
Naphthas:					
Very Light (C5-160)	0.049	0.049	0.060	0.024	0.052
Light (160-250)	0.075	0.063	0.049	0.041	0.090
Medium (250-325)	0.070	0.056	0.040	0.041	0.081
Heavy (325-375)	0.046	0.037	0.028	0.029	0.050
Middle Distillates:					
Kerosene (375-500)	0.118	0.099	0.074	0.086	0.130
Distillate (500-620)	0.121	0.115	0.109	0.104	0.126
Atmospheric Resid:					
Light gas oil (620-800)	0.163	0.165	0.170	0.161	0.163
Heavy gas oil (800-1050)	0.168	0.174	0.176	0.191	0.162
Resid (1050+)	0.173	0.224	0.275	0.317	0.124
SULFUR (wt%)					
Kerosene (375-500)	0.25%	0.35%	0.49%	0.55%	0.19%
Distillate (500-620)	0.68%	0.83%	1.05%	1.19%	0.46%
Gas Oils (620-1050)	1.49%	1.87%	2.57%	2.08%	1.00%
Resid (1050+)	3.59%	4.46%	5.99%	3.76%	2.14%

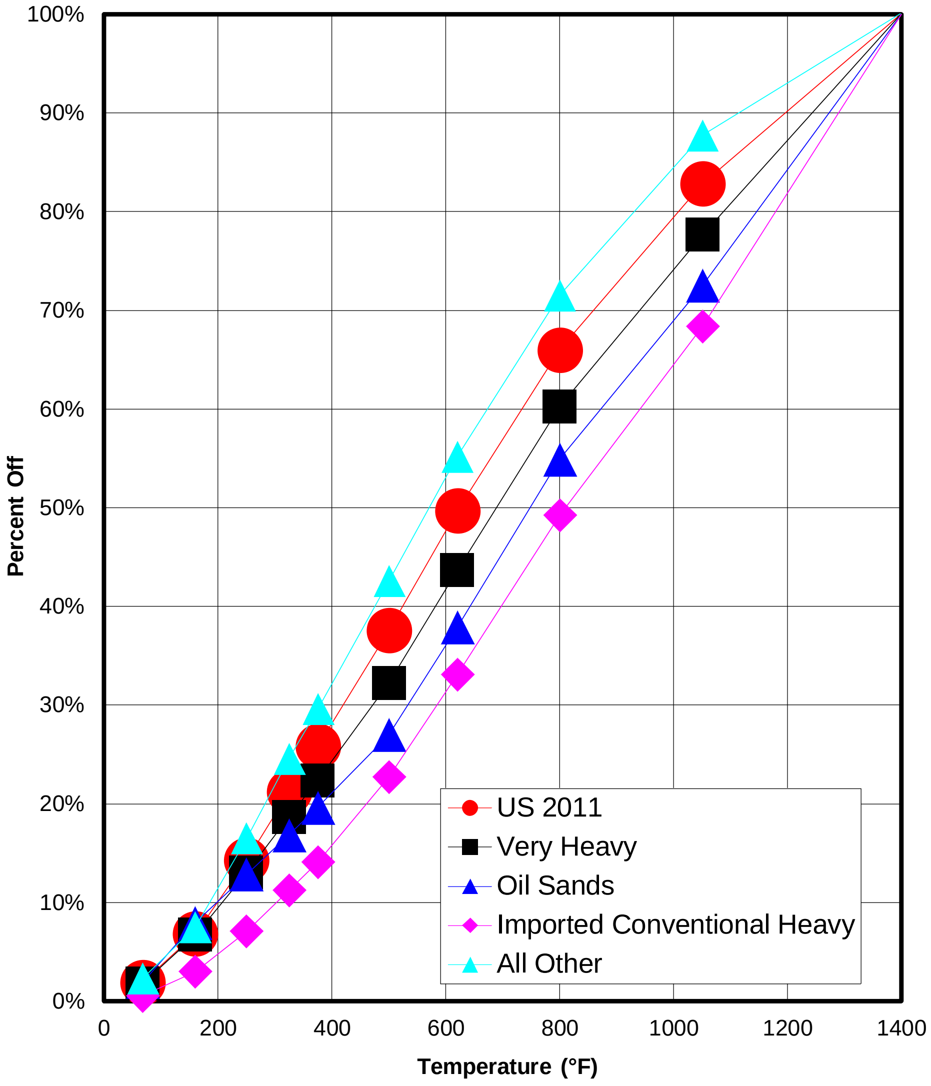


Exhibit 6.2: Distillation Curves and Whole Crude Properties for Components of the Import Independence Crude Slate

Crude Fractions and Properties	2011 U.S. Crude Slate	Import Indep. Crude Slate	Components		
			Light Tight Oil	Oil Sands Crudes	All Other
WHOLE CRUDE					
API Gravity	30.5	31.1	44.2	22.0	34.1
Sulfur (wt %)	1.41%	1.63%	0.12%	3.09%	0.88%
CRUDE FRACTIONS					
LPGs:					
Ethane	0.001	0.000	0.000	0.000	0.001
Propane	0.003	0.003	0.003	0.001	0.004
Isobutane	0.004	0.005	0.005	0.005	0.004
Butane	0.012	0.014	0.011	0.014	0.014
Naphthas:					
Very Light (C5-160)	0.049	0.061	0.083	0.060	0.051
Light (160-250)	0.075	0.078	0.114	0.049	0.088
Medium (250-325)	0.070	0.071	0.112	0.040	0.079
Heavy (325-375)	0.046	0.044	0.060	0.028	0.050
Middle Distillates:					
Kerosene (375-500)	0.118	0.111	0.147	0.074	0.128
Distillate (500-620)	0.121	0.120	0.131	0.109	0.124
Atmospheric Resid:					
Light gas oil (620-800)	0.163	0.164	0.156	0.170	0.162
Heavy gas oil (800-1050)	0.168	0.163	0.134	0.176	0.164
Resid (1050+)	0.173	0.169	0.044	0.275	0.131
SULFUR (wt%)					
Kerosene (375-500)	0.25%	0.23%	0.02%	0.49%	0.21%
Distillate (500-620)	0.68%	0.60%	0.08%	1.05%	0.49%
Gas Oils (620-1050)	1.49%	1.56%	0.22%	2.57%	1.10%
Resid (1050+)	3.59%	4.59%	0.64%	5.99%	2.45%

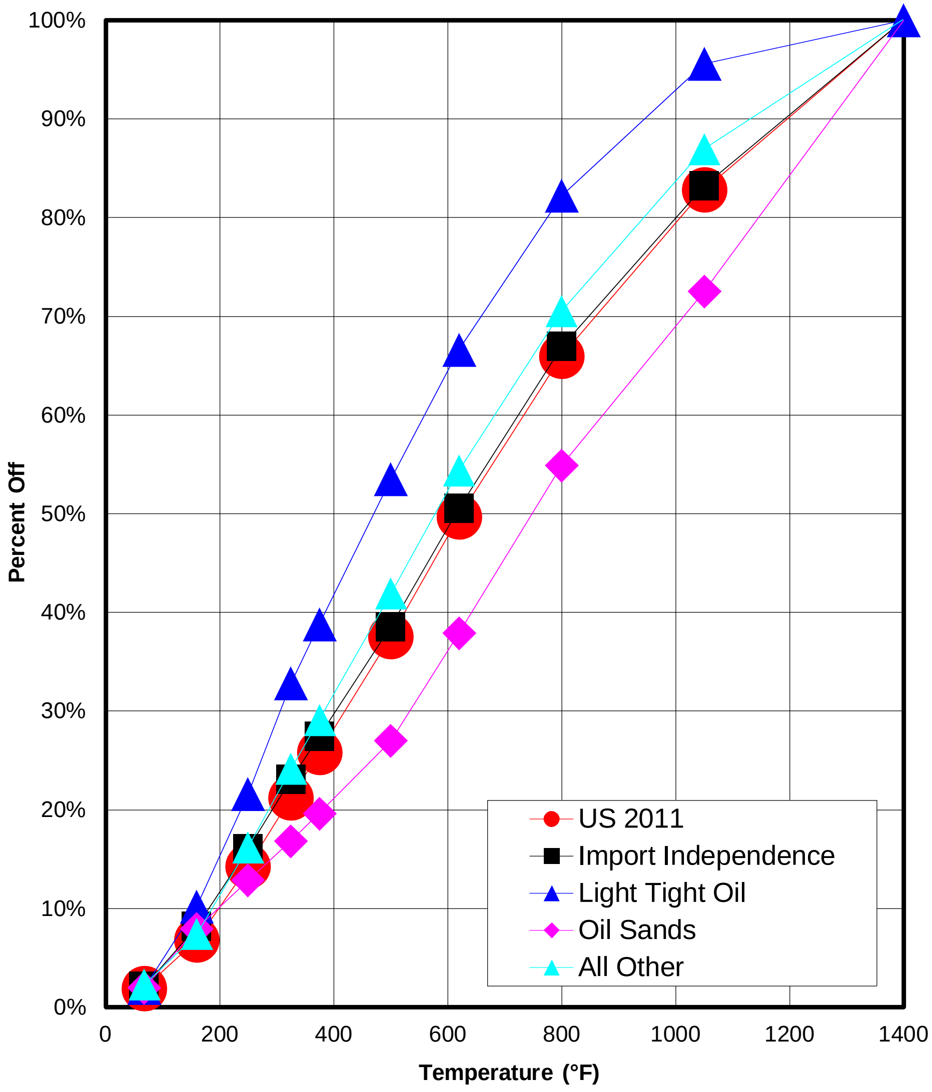


Exhibit 6.3: Distillation Curves and Whole Crude Properties for Components of the Very Light Crude Slate

Crude Fractions and Properties	2011 U.S. Crude Slate	Very Light Crude Slate	Components		
			Light Tight Oil	Imported Light & Medium	All Other
WHOLE CRUDE					
API Gravity	30.5	35.5	44.2	35.2	31.6
Sulfur (wt %)	1.41%	0.93%	0.12%	0.95%	1.30%
CRUDE FRACTIONS					
LPGs:					
Ethane	0.001	0.001	0.000	0.001	0.001
Propane	0.003	0.004	0.003	0.005	0.003
Isobutane	0.004	0.004	0.005	0.004	0.004
Butane	0.012	0.013	0.011	0.014	0.014
Naphthas:					
Very Light (C5-160)	0.049	0.061	0.083	0.057	0.052
Light (160-250)	0.075	0.090	0.114	0.084	0.080
Medium (250-325)	0.070	0.084	0.112	0.080	0.072
Heavy (325-375)	0.046	0.052	0.060	0.057	0.045
Middle Distillates:					
Kerosene (375-500)	0.118	0.130	0.147	0.135	0.118
Distillate (500-620)	0.121	0.127	0.131	0.129	0.123
Atmospheric Resid:					
Light gas oil (620-800)	0.163	0.162	0.156	0.159	0.167
Heavy gas oil (800-1050)	0.168	0.156	0.134	0.160	0.165
Resid (1050+)	0.173	0.117	0.044	0.113	0.157
SULFUR (wt%)					
Kerosene (375-500)	0.25%	0.16%	0.16%	0.62%	0.62%
Distillate (500-620)	0.68%	0.44%	0.44%	1.38%	1.26%
Gas Oils (620-1050)	1.49%	1.08%	1.08%	3.03%	2.89%
Resid (1050+)	3.59%	3.21%	3.21%	5.99%	5.94%

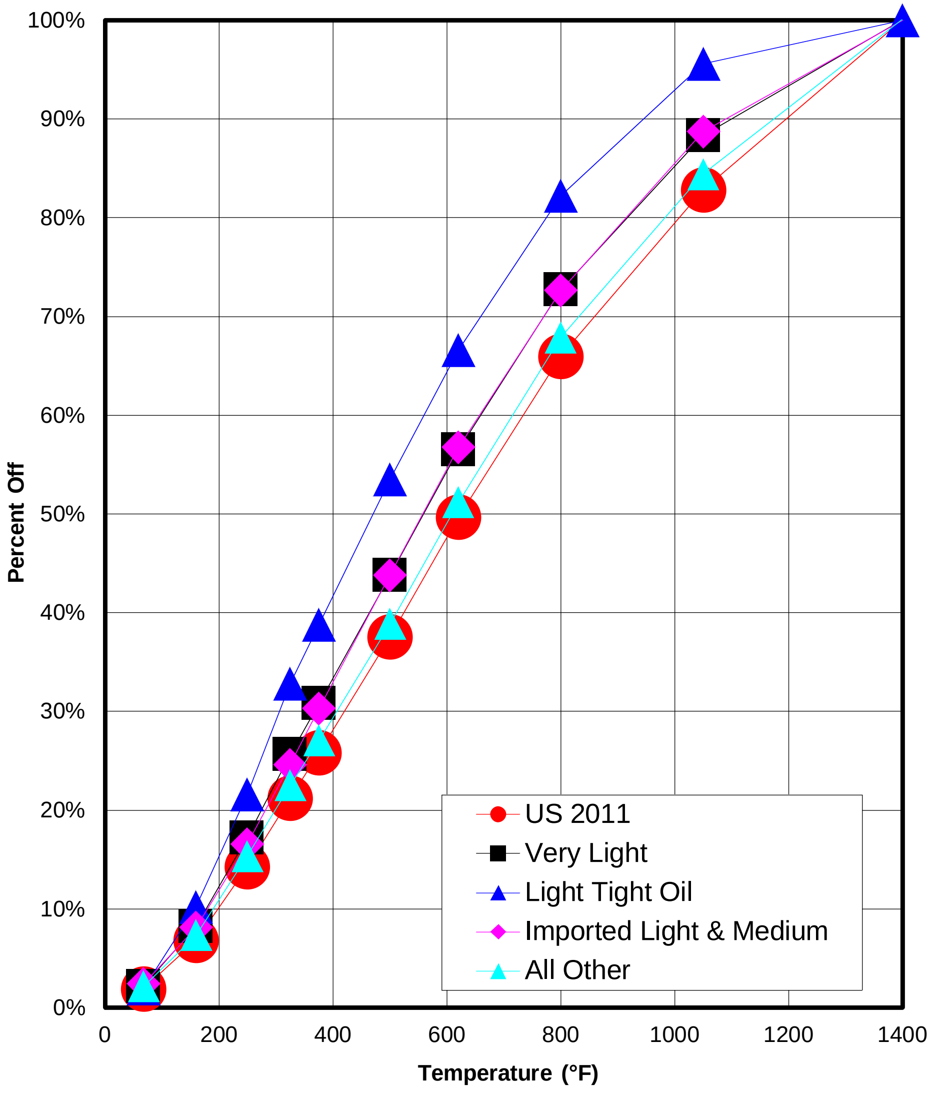


Exhibit 7: CAPP-Projected Production and Supply of Canadian Crude Oil (K b/d)

Source, Destinations, and Type of Crude Oil	Reported 2011	Projected			
		2015	2020	2025	2030
WESTERN CANADA					
PRODUCTION					
Pentanes/Condensate	**142**	**124**	**111**	**100**	**92**
Conventional Crude Oil	**991**	**1,211**	**1,210**	**1,145**	**1,045**
Light & Medium	610	818	831	781	694
Heavy	382	393	379	365	351
Oil Sands -- Raw Bitumen[1]	**1,745**	**2,481**	**3,389**	**4,497**	**5,326**
Mining	892	1,214	1,524	1,927	2,170
In-Situ	852	1,267	1,865	2,570	3,155
Product Streams -- Post-Upgrading[2]	**1,615**	**2,299**	**3,165**	**4,215**	**5,020**
Mining	772	1,061	1,327	1,676	1,891
In-Situ	844	1,238	1,838	2,539	3,129
BLENDED MARKET SUPPLY					
Western Canada & Ontario[5]	**875**	**960**	**971**	**981**	**992**
United States	**2,032**	**2,918**	**3,964**	**5,187**	**5,868**
Conventional					
Light & Medium	228	415	427	400	355
Heavy	263	267	270	264	254
Oil Sands					
Synthetic (Light)[3]	446	742	825	883	745
Heavy[4]	1,095	1,494	2,442	3,639	4,514
Conventional Heavy	6%	4%	3%	2%	2%
Synthetic	5%	4%	9%	13%	17%
Condensate	23%	20%	20%	20%	16%
In-situ bitumen	66%	71%	68%	65%	65%
Other[6]	**11**	**11**	**11**	**11**	**11**
EASTERN CANADA					
Conventional Crude Production					
Light & Medium	268	216	216	161	86
Blended Market Supply					
Eastern Canada & Exports	146	146	146	146	86
United States	122	70	70	15	0

Notes: Excludes crude oil production in Newfoundland. Difference between crude oil production and supply mostly reflects the use of imported of light blending components, such as condensate.

1 Total volume of produced-bitumen directly blended in crude oil or used as upgrader feed.

2 Includes synthetic crude oil, upgraded bitumen, and raw in-situ bitumen.

3 Includes small volume of upgraded conventional crude oil.

4 Includes dilbit, synbit, and Western Canadian Select crude oils.

5 Supply to Western Canada and Ontario is assumed to grow at the rate of 0.55% per year after 2015. Supply over the perion 2011-2015 is based on CAPP projections.

6 Supply to other areas is assumed to be light & medium conventional crudes and to remain unchanged.

Sources: Derived from Appendices B.1 & B.3, *Crude Oil Forecast, Markets & Pipeliines, 2012*, Canadian Association of Petroleum Producers, June 2012; and Refiner Survey, CAPP Website.

Exhibit 8: Assumptions Underlying Alternative Refined Product Slates

Primary Refined Products	Refined Product Slate Designation				
	2025				2035
	Current CAFÉ Standards	New CAFÉ Standards	New CAFÉ Standards		
			Low Bio Diesel	Low Bio Diesel	
				High Ethanol	High Ethanol
Gasoline	AEO Ref Adjusted for Current CAFÉ	AEO Ref	AEO Ref	AEO Ref adjusted for partial Phase-in of 30% Ethanol	AEO Ref adjusted for full Phase-in of 30% Ethanol
Jet Fuel	AEO Ref	AEO Ref	AEO Ref	AEO Ref	AEO Ref
Diesel Fuel	AEO Ref	AEO Ref	AEO Ref with no increase in bio or other diesel liquids	AEO Ref with no increase in bio or other diesel liquids	AEO Ref with no increase in bio or other diesel liquids
Residual Oil	MARPOL Stds	MARPOL Stds	MARPOL Stds	MARPOL Stds	MARPOL Stds
Resulting G/D Ratio	Base	Low	Lower	Very Low	Extremely Low

Exhibit 9: Composition of Alternative Product Slates
(K b/d)

Primary Refined Products	2011	2025				2035
		Current CAFÉ Standards[1]	New CAFÉ Standards	New CAFÉ Standards		
				Low Bio Diesel	Low Bio Diesel	
					High Ethanol	High Ethanol
Total Petroleum Products	**15,651**	**15,890**	**15,121**	**15,255**	**14,888**	**14,218**
Liquified Petroleum Gases	**572**	**559**	**559**	**559**	**559**	**547**
Ethane-Ethylene	20	20	20	20	20	20
Propane	270	276	276	276	276	270
Propylene	282	264	264	264	264	258
Finished Refined Products[2]	**15,080**	**15,331**	**14,562**	**14,695**	**14,329**	**13,671**
BOBs & Finished Gasoline	7,623	7,532	6,763	6,763	6,396	5,514
BOBs						
Reformulated						
E10	2,185				939	
E15		2,025	1,805	1,805		
E30					784	1,453
Conventional						
E10	3,038	3,614	3,221	3,221	2,299	
E15		1,409	1,256	1,256		
E30					1,919	3,576
E85		29	26	26		
Finished Conventional[3]						
Domestic	1,921					
Export	479	456	456	456	456	486
Aviation Gasoline	15	14	14	14	14	14
Jet Fuel	1,459	1,550	1,550	1,550	1,550	1,625
Kerosene	15	15	15	15	15	15
Distillate[4]	4,470	4,946	4,946	5,080	5,080	5,176
0-15 ppm Sulfur	3,624	4,280	4,280	4,405	4,405	4,541
15-500 ppm Sulfur	177					
> 500 ppm Sulfur	408	409	409	409	409	367
CARB Diesel	262	257	257	266	266	268
Low Sulfur Marine Fuel				376	376	406
Residual Fuel Oil	530	376	376			
Pet Chem Feedstocks						
Naphtha	206	192	192	192	192	196
Other Oils	101	94	94	94	94	96
Special Naphtha	38	35	35	35	35	36
Lubes & Waxes	178	165	165	165	165	170
Asphalt and Road Oil	365	339	339	339	339	347
Miscellaneous Non-Fuel Use	79	73	73	73	73	75
Petroleum Coke						
Marketable	615	571	571	571	571	585
Catalyst	228	211	211	211	211	217
G/D Ratio	**1.28**	**1.16**	**1.04**	**1.02**	**0.96**	**0.81**

Note: BOB stands for gasoline blendstock for oxygenate blending. BOBs are formulated with properties such that the finished blended gasoline meets octane requirements, RVP standards, and reformulated gasoline standards, when applicable.

[1] Estimates from prior work indicate that gasoline consumption would be about 12% higher with the old CAFÉ standards.

[2] Excludes petroleum coke, still gas, and miscellaneous fuel use

[3] Finished gasoline meets minimum octane requirements. Much of the finished domestic gasoline subsequently is blended with 10 vol% ethanol.

[4] Excludes bio-diesel and distillates produced -from gas, coal, or biomass.

Source: Derived from refinery output and export data from EIA's Website; projections based on *AEO 2012* , and previous MathPro Studies.

Exhibit 10a: Annual CO2 Emissions, by Crude Slate

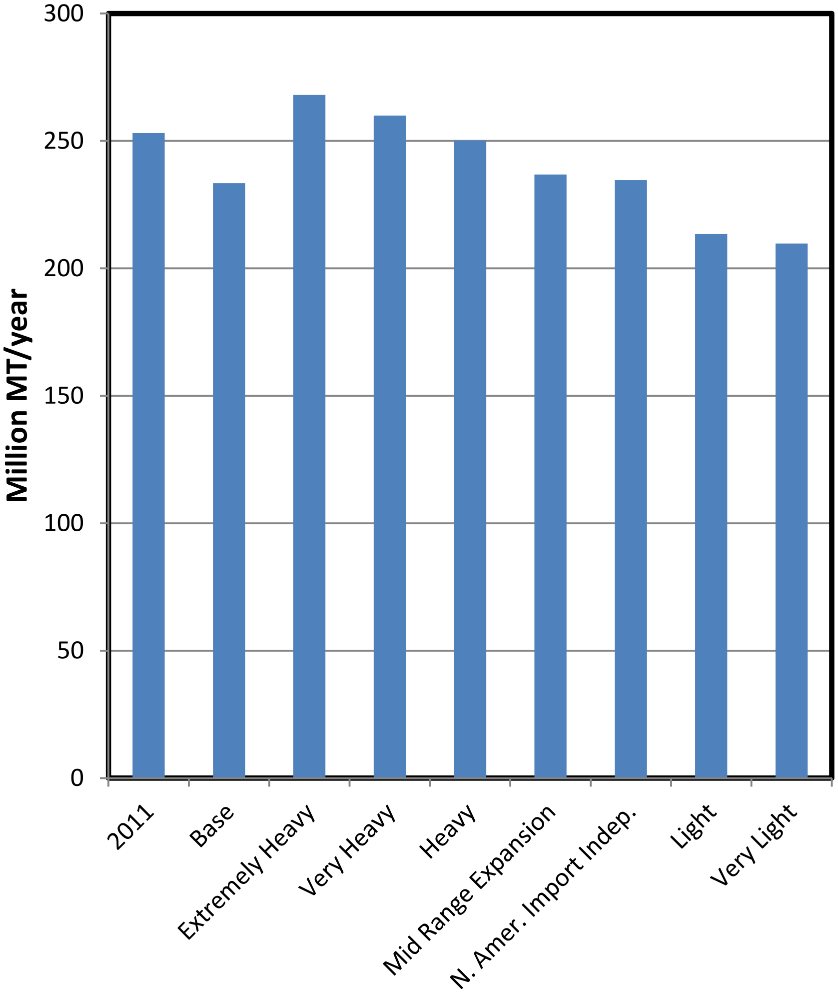
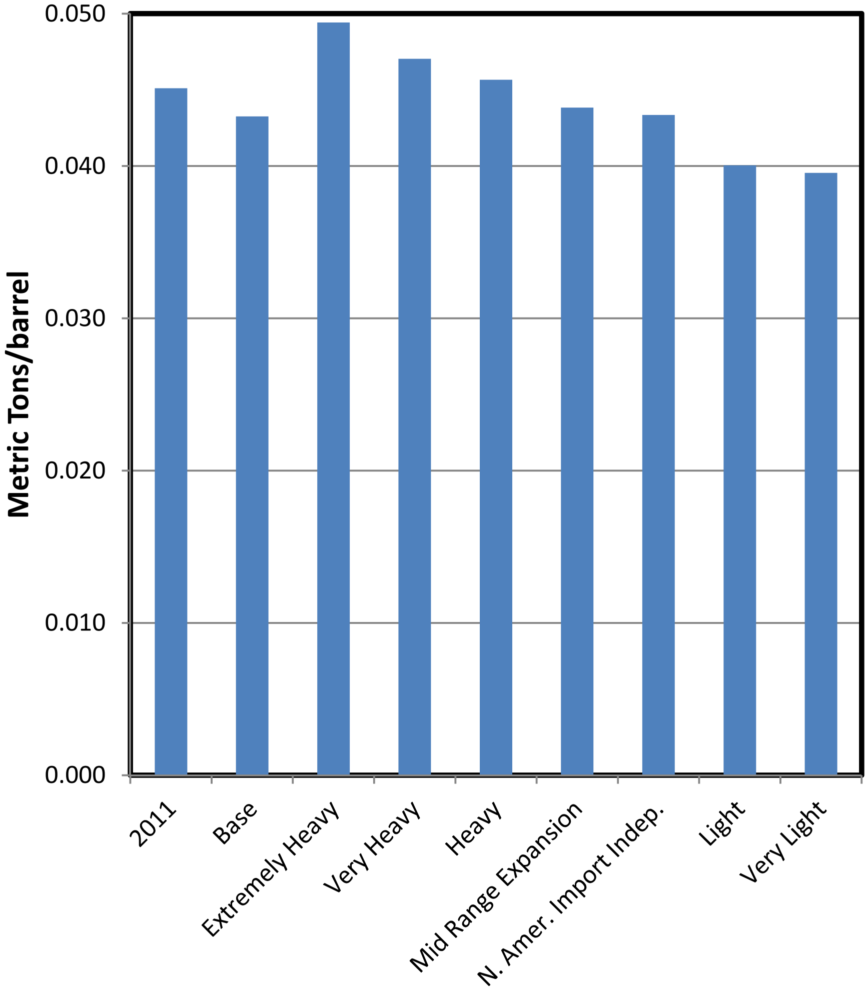


Exhibit 10b: CO2 Emissions per Barrel of Crude, by Crude Slate



Note: Crude includes purchased gas oils and residuum.

Exhibit 10c: Annual Energy Use, by Crude Slate

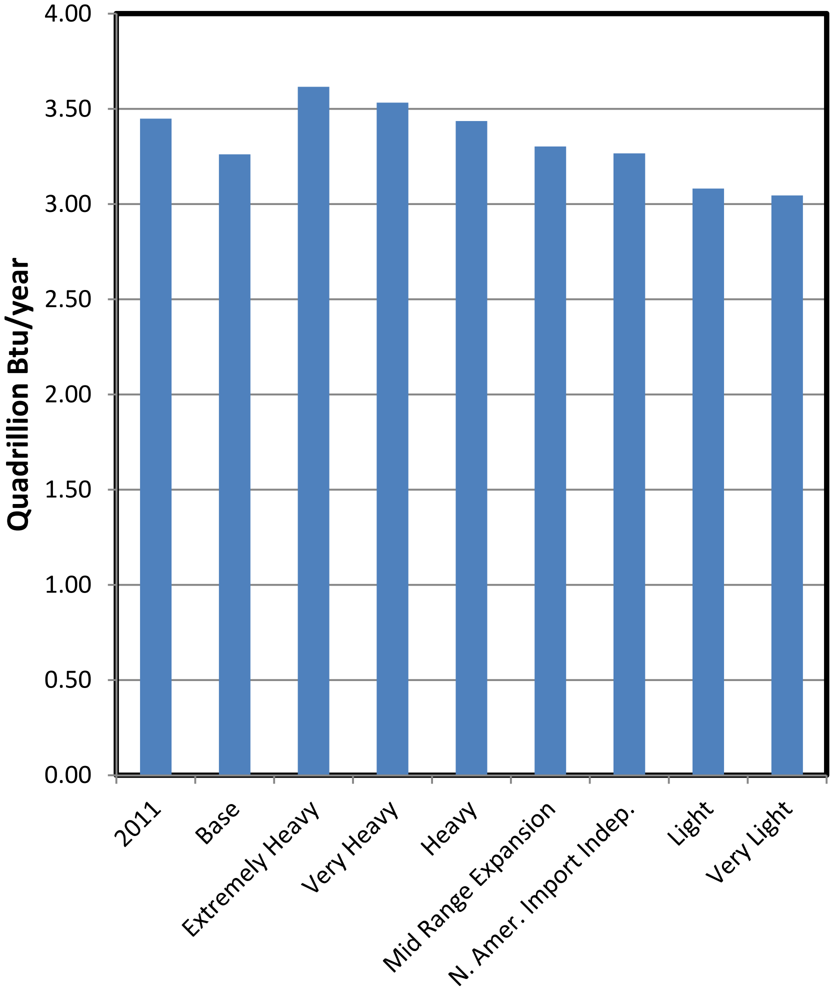
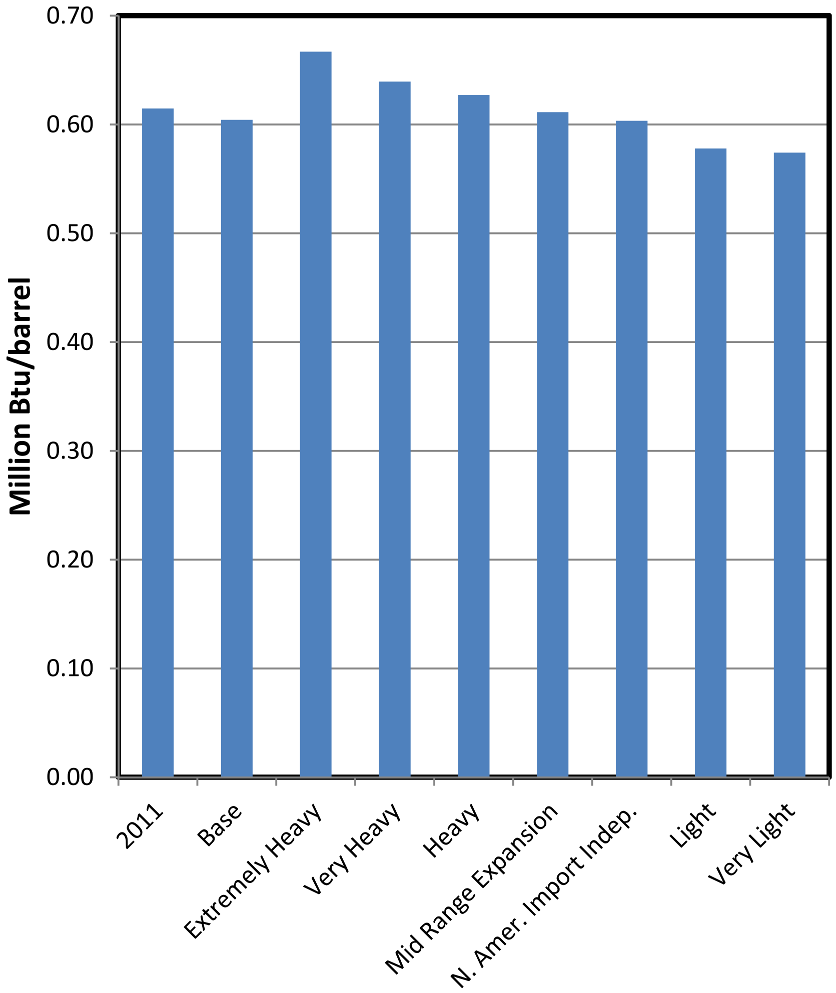


Exhibit 10d: Energy Use per Barrel of Crude, by Crude Slate



Note: Crude includes purchased gas oils and residuum.

Exhibit 11: Refinery Inputs, Purchased Energy, Outputs, Fuel Use, Energy Use, and CO2 Emissions --

2025 Projected Product Slate with New CAFÉ Standards

	2011	Crude Slate							
Inputs & Outputs	**Calib**	**Base**	**Ext. Heavy**	**Very Heavy**	**Heavy**	**Mid Expan**	**Import Indep**	**Light**	**Very Light**
Inputs (K b/d)									
Crude Oil	14,712	14,314	14,383	14,664	14,540	14,327	14,354	14,131	14,057
C4s	234	170	246	170	170	170	170	170	170
NGL, Naphtha & Gas Blndstk.	209	302	302	302	302	302	302	302	302
Heavy Gas Oil & Resid	661	474	474	474	474	474	474	474	474
Purchased Energy									
Electricity (MM Kwh/d)	172	167	190	183	177	170	167	155	154
Natural Gas (K foeb/d)	612	642	783	715	703	665	664	631	636
Outputs (K b/d)[1]	**15,682**	**15,105**	**15,113**	**15,108**	**15,101**	**15,094**	**15,089**	**15,082**	**15,082**
Light Gases	583	542	550	545	538	531	526	519	519
Aromatics, Naphthas, & Av Gas	259	241	241	241	241	241	241	241	241
Hydrocarbon Gasoline	7,623	6,764	6,764	6,764	6,764	6,764	6,764	6,764	6,764
Jet Fuel	1,493	1,565	1,565	1,565	1,565	1,565	1,565	1,565	1,565
Diesel Fuel	4,471	4,946	4,946	4,946	4,946	4,946	4,946	4,946	4,946
Resid & Asphalt	895	715	715	715	715	715	715	715	715
All Other Liquids	358	332	332	332	332	332	332	332	332
Coke	590	690	1,015	1,109	940	731	692	456	361
Sulfur (K s tons/d)	20	19	23	29	26	20	21	13	12
Fuel Use									
Natural Gas (K foeb/d)	437	470	496	458	474	481	479	509	522
Still Gas (K foeb/d)	569	530	641	653	601	539	529	447	419
Catalyst Coke (K b/d)	232	160	141	140	144	155	155	145	145
Energy Use (Billion btu/d)	**9,449**	**8,935**	**9,908**	**9,680**	**9,414**	**9,048**	**8,948**	**8,441**	**8,342**
Fuel (incl. cat coke)	7,733	7,266	8,010	7,849	7,644	7,356	7,284	6,892	6,801
Power	1,716	1,669	1,898	1,830	1,771	1,692	1,664	1,549	1,541
CO2 Emissions (K MT/d)	**693**	**640**	**734**	**712**	**685**	**649**	**643**	**585**	**575**
Natural Gas & Still Gas	376	372	425	418	402	379	374	351	344
Catalyst Coke	145	100	88	88	90	97	97	91	91
Power	110	107	121	117	113	108	106	99	99
On-Purpose Hydrogen	62	61	100	90	80	65	65	44	41
CO2 Emissions/Crude Oil Input									
Metric Tons/Barrel	0.045	0.043	0.049	0.047	0.046	0.044	0.043	0.040	0.040
Grams/Megajoule	7.3	7.2	8.0	7.7	7.6	7.3	7.3	6.8	6.7
Crude Oil Properties									
API Gravity	30.5	30.5	24.6	26.3	28.2	30.0	31.1	34.2	35.5
Specific Gravity	0.873	0.873	0.907	0.897	0.886	0.876	0.870	0.854	0.847
Sulfur Content (wt%)	1.41	1.41	1.49	2.04	1.90	1.49	1.63	1.02	0.93
Est. Energy Density (MM btu/b)	5.870	5.870	6.021	5.951	5.908	5.880	5.847	5.798	5.771

[1] Total excludes coke and sulfur.

Exhibit 12: Summary of Refining Process Operations --
2025 Projected Product Slate with New CAFÉ Standards

		2011	Crude Slate							
Process	**Description**	**Calib**	**Base**	**Ext. Heavy**	**Very Heavy**	**Heavy**	**Mid Expan**	**Import Indep**	**Light**	**Very Light**
Use of In-Place Capacity										
Atmos Distillation	Throughput (K b/d)	14,712	14,314	14,383	14,664	14,540	14,327	14,354	14,131	14,057
	Percent of In-Place Capacity (%)	83%	88%	88%	90%	89%	88%	88%	87%	86%
Conversion Processes										
Fluid Cat Cracker	Charge Rate (K b/d)	4,769	3,484	3,070	3,116	3,127	3,366	3,163	3,218	3,102
	Conversion (Vol %)	70.5	68.5	77.3	71.4	71.2	68.8	68.9	68.2	68.1
	Percent of In-Place Capacity (%)	84%	65%	57%	58%	58%	63%	59%	60%	58%
Hydrocracker	Charge Rate (K b/d)	1,340	1,935	2,898	2,325	2,269	2,045	2,115	1,867	1,925
	Kero & Dist. as % of Out-turns (%)	29.8	44.0	48.1	47.6	49.0	45.1	49.3	45.3	44.6
	Percent of In-Place Capacity (%)	100%	131%	196%	157%	153%	138%	143%	126%	130%
Coking	Charge Rate (K b/d)	2,109	2,280	3,188	3,321	2,872	2,358	2,224	1,661	1,418
	Percent of In-Place Capacity (%)	83%	85%	119%	124%	107%	88%	83%	62%	53%
Upgrading Processes										
Alkylation	Output (K b/d)	1,160	1,009	1,093	1,077	1,068	1,020	1,032	959	951
	Percent of Capacity (%)	100%	92%	100%	99%	98%	93%	94%	88%	87%
Reforming	Charge Rate (K b/d)	2,723	2,593	2,417	2,538	2,571	2,683	2,622	2,782	2,896
	Percent of Capacity (%)	77%	77%	72%	75%	76%	79%	78%	82%	86%
	Severity	95.4	92.7	92.0	92.2	93.0	92.2	94.1	93.7	92.9
Pen-Hex Isomerization	Charge Rate (K b/d)	534	548	548	548	548	548	548	548	548
	Percent of Capacity (%)	100%	100%	100%	100%	100%	100%	100%	100%	100%
Hydrogen (MM scf/d)	On-Purpose Hydrogen Production	4,523	4,430	7,255	6,513	5,832	4,720	4,742	3,217	3,002
	Percent of Capacity (%)	100%	97%	158%	142%	127%	103%	104%	70%	66%
New Capacity										
Vacuum Distillation				1,049	773	353				
Hydrocracking			504	1,574	937	874	626	703	428	492
Coking				563	711	211				
Benzene Saturation			10		12	34	41	55	88	83
FCC Feed Desulfurization				516						
Hydrogen Plant (MM scf/d)				2,973	2,149	1,392	156	181		
Butane Isomerization			80	8	122	122	90	101	74	68
Retrofits										
Diesel Desulf/Dearom			305	6	180	305	386	217	264	304
FCC High Distillate Yield			615		779	581	602	164	432	

Note: In-place refining capacity for 2025 includes planned refinery expansions and announced closures as of 2011, and future closures of smaller, less complex refineries to maintain an approximate 87% utilization of atmospheric distillation capacity, as projected in *AEO 2013*.

Exhibit 13: Finished Gasoline Pool Properties and Composition --
2025 Projected Product Slate with New CAFÉ Standards

Gasoline Properties, Composition, & Volume	2011	Crude Slate							
	Calib	Base	Ext. Heavy	Very Heavy	Heavy	Mid Expan	Import Indep	Light	Very Light
Properties									
RVP (psi)	10.6	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
Oxygen (wt%)	3.2	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3
Aromatics (vol%)	19.4	16.5	16.5	16.1	16.1	16.3	16.4	17.1	17.0
Benzene (vol%)	0.58	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
Olefins (vol%)	7.9	5.3	5.5	5.1	5.0	5.1	4.6	4.8	4.5
Sulfur (ppm)	21	9	9	9	9	9	9	9	9
E200 (vol% off)	53.2	56.8	54.4	56.3	56.7	56.7	57.1	57.0	57.8
E300 (vol% off)	84.4	85.9	84.4	85.3	86.1	86.0	86.6	86.5	86.5
Energy Density (MM btu/b)	5.012	4.898	4.877	4.865	4.878	4.895	4.897	4.919	4.925
Octane ((R+M)/2)	88.7	88.3	88.3	88.3	88.3	88.3	88.3	88.3	88.3
Composition (%)	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
C4s	4.9	4.7	5.2	4.8	4.6	4.6	4.4	4.5	4.4
C5s & Isomerate	6.2	7.0	7.0	7.0	7.0	7.0	7.0	7.0	7.0
Raffinate	0.7	0.9	0.8	0.7	0.7	0.8	0.6	0.7	0.7
Naphthas & NGLs (C5-250°)	8.9	11.8	10.2	12.3	13.1	11.3	14.2	12.7	12.1
Hydrocrackate	4.5	5.7	6.7	6.1	5.8	5.9	5.5	5.6	5.7
Alkylate	13.6	12.8	13.8	13.4	13.3	12.9	12.9	12.0	11.9
Iso-Octane/Octene	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
FCC Naphtha	27.3	18.9	19.5	17.8	17.2	18.0	16.7	17.1	16.4
Reformate & Aromatics	24.3	25.5	24.1	25.2	25.5	26.9	26.0	27.7	29.2
Ethanol[1]	9.4	12.6	12.6	12.6	12.6	12.6	12.6	12.6	12.6
Volume (K b/d)	**8412**	**7736**	**7736**	**7736**	**7736**	**7736**	**7736**	**7736**	**7736**

Note: Includes finished domestic reformulated and conventional gasoline, E85, and export gasoline.

[1] Ethanol that subsequently may have been blended in finished, non-oxygenated, gasoline that refineries reported producing in 2011 is not included; only ethanol blended in BOBs is included.

Exhibit 14: Distillate Properties and Composition -- 2025 Projected Product Slate with New CAFÉ Standards

Distillate Properties & Composition	2011	Crude Slate							
	Calib	Base	Ext. Heavy	Very Heavy	Heavy	Mid Expan	Import Indep	Light	Very Light
Properties									
Sulfur Content (ppm)	349	318	318	316	317	317	319	319	318
Cetane Number (Diesel only)	44.0	43.7	42.9	43.0	43.4	43.6	43.9	44.8	45.3
Aromatics (vol%)	28.4	28.3	27.7	29.5	29.2	29.0	28.1	26.6	25.8
API Gravity	37.5	37.4	36.2	36.3	36.7	37.1	37.4	38.2	38.5
E450 (% off)	35	35	32	33	33	34	34	36	36
E500 (% off)	57	56	52	53	53	55	54	57	57
E600 (% off)	91	91	91	91	91	91	91	91	91
Composition (%)	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
Straight Run									
Heavy Naphtha	11	10	8	9	9	10	10	11	12
Kerosene	28	25	21	22	22	24	24	27	27
Distillate	25	23	22	24	24	24	25	24	24
Hydrocracked									
Jet	9	12	13	13	12	12	11	11	12
Distillate		4	12	8	8	5	8	5	5
Coker Distillate	10	9	12	12	10	9	8	7	6
FCC									
Heavy Naphtha	2	3	2	2	3	3	3	3	3
Light Cycle Oil	15	14	8	10	10	13	11	13	12
Volume (K b/d)	**5964**	**6511**	**6511**	**6511**	**6511**	**6511**	**6511**	**6511**	**6511**

Exhibit 15a: Summary of CO2 Emissions and Energy Use, by Crude Oil Slate and Product Slate

Product Slate & Measure of Emissions	Crude Slate							
	Base	**Ext. Heavy**	**Very Heavy**	**Heavy**	**Mid Expan**	**Import Indep**	**Light**	**Very Light**
Current CAFÉ Standards								
CO2 Emissions								
Million MT/y	246	286	276	265	249	252	226	221
Metric tons/b crude	0.044	0.050	0.048	0.046	0.044	0.044	0.041	0.040
Energy Use								
Quadrillion Btu/y	3.42	3.87	3.75	3.63	3.47	3.49	3.24	3.19
Million Btu/b crude	0.606	0.678	0.647	0.632	0.613	0.615	0.582	0.575
New CAFÉ Standards								
CO2 Emissions								
Million MT/y	233	268	260	250	237	235	213	210
Metric tons/b crude	0.043	0.049	0.047	0.046	0.044	0.043	0.040	0.040
Energy Use								
Quadrillion Btu/y	3.26	3.62	3.53	3.44	3.30	3.27	3.08	3.04
Million Btu/b crude	0.604	0.667	0.639	0.627	0.611	0.603	0.578	0.574
Low Biodiesel Volume								
CO2 Emissions								
Million MT/y	234	271	261	251	237	235	214	210
Metric tons/b crude	0.043	0.049	0.047	0.045	0.043	0.043	0.040	0.039
Energy Use								
Quadrillion Btu/y	3.27	3.65	3.56	3.45	3.31	3.28	3.08	3.05
Million Btu/b crude	0.599	0.668	0.637	0.623	0.606	0.600	0.573	0.570
Partial E30								
CO2 Emissions								
Million MT/y	226	263	253	243	229	228	208	206
Metric tons/b crude	0.042	0.049	0.046	0.045	0.043	0.043	0.039	0.039
Energy Use								
Quadrillion Btu/y	3.17	3.57	3.46	3.35	3.21	3.19	3.01	2.98
Million Btu/b crude	0.595	0.666	0.634	0.619	0.602	0.597	0.572	0.568
Full E30								
CO2 Emissions								
Million MT/y	204	242	230	218	206	210	196	195
Metric tons/b crude	0.040	0.047	0.044	0.042	0.040	0.041	0.038	0.038
Energy Use								
Quadrillion Btu/y	2.93	3.30	3.19	3.08	2.96	2.97	2.80	2.77
Million Btu/b crude	0.572	0.641	0.608	0.590	0.577	0.573	0.549	0.546
Sensitivity Cases								
High Biojet								
CO2 Emissions								
Million MT/y	229	263	256	248	232	233	208	206
Metric tons/b crude	0.044	0.050	0.048	0.047	0.044	0.044	0.040	0.040
Energy Use								
Quadrillion Btu/y	3.19	3.55	3.47	3.40	3.23	3.23	2.99	2.97
Million Btu/b crude	0.612	0.675	0.649	0.640	0.619	0.616	0.580	0.576
No Petroleum Coke								
CO2 Emissions								
Million MT/y	274	319	317	303	278	277	244	234
Metric tons/b crude	0.054	0.064	0.063	0.060	0.055	0.054	0.048	0.045
Energy Use								
Quadrillion Btu/y	3.69	4.17	4.12	4.00	3.72	3.71	3.40	3.30
Million Btu/b crude	0.723	0.840	0.820	0.787	0.730	0.726	0.663	0.642

Exhibit 15b: Percent Change in CO2 Emissions and Energy Use Relative to Base Crude Slate, by Product Slate

Product Slate & Measure of Emissions	Crude Slate							
	Base	Ext. Heavy	Very Heavy	Heavy	Mid Expan	Import Indep	Light	Very Light
Current CAFÉ Standards								
CO2 Emissions								
Million MT/y	-	16%	12%	8%	1%	2%	-8%	-10%
Metric tons/b crude	-	15%	9%	6%	1%	2%	-7%	-8%
Energy Use								
Quadrillion Btu/y	-	13%	10%	6%	1%	2%	-5%	-7%
Million Btu/b crude	-	12%	7%	4%	1%	2%	-4%	-5%
New CAFÉ Standards								
CO2 Emissions								
Million MT/y	-	15%	11%	7%	1%	0%	-9%	-10%
Metric tons/b crude	-	14%	9%	6%	1%	0%	-7%	-9%
Energy Use								
Quadrillion Btu/y	-	11%	8%	5%	1%	0%	-6%	-7%
Million Btu/b crude	-	10%	6%	4%	1%	0%	-4%	-5%
Low Biodiesel Volume								
CO2 Emissions								
Million MT/y	-	16%	12%	7%	1%	1%	-9%	-10%
Metric tons/b crude	-	15%	9%	6%	1%	0%	-7%	-8%
Energy Use								
Quadrillion Btu/y	-	12%	9%	6%	1%	0%	-6%	-7%
Million Btu/b crude	-	11%	6%	4%	1%	0%	-4%	-5%
Partial E30								
CO2 Emissions								
Million MT/y	-	16%	12%	7%	1%	1%	-8%	-9%
Metric tons/b crude	-	16%	9%	6%	1%	0%	-7%	-7%
Energy Use								
Quadrillion Btu/y	-	12%	9%	6%	1%	1%	-5%	-6%
Million Btu/b crude	-	12%	7%	4%	1%	0%	-4%	-4%
Full E30								
CO2 Emissions								
Million MT/y	-	18%	12%	7%	1%	3%	-4%	-5%
Metric tons/b crude	-	18%	10%	5%	1%	1%	-4%	-4%
Energy Use								
Quadrillion Btu/y	-	13%	9%	5%	1%	1%	-4%	-5%
Million Btu/b crude	-	12%	6%	3%	1%	0%	-4%	-5%
Sensitivity Cases								
High Biojet								
CO2 Emissions								
Million MT/y	-	15%	12%	8%	1%	2%	-9%	-10%
Metric tons/b crude	-	14%	9%	6%	1%	1%	-8%	-9%
Energy Use								
Quadrillion Btu/y	-	11%	9%	7%	1%	1%	-6%	-7%
Million Btu/b crude	-	10%	6%	5%	1%	1%	-5%	-6%
No Petroleum Coke								
CO2 Emissions								
Million MT/y	-	16%	15%	10%	1%	1%	-11%	-15%
Metric tons/b crude	-	20%	17%	11%	2%	1%	-11%	-15%
Energy Use								
Quadrillion Btu/y	-	13%	12%	8%	1%	1%	-8%	-10%
Million Btu/b crude	-	16%	13%	9%	1%	0%	-8%	-11%

Exhibit 15c: Percent Change in CO2 Emissions and Energy Use Relative to New CAFE Standard Product Slate, by Crude Slate

Product Slate & Measure of Emissions	Crude Slate							
	Base	Ext. Heavy	Very Heavy	Heavy	Mid Expan	Import Indep	Light	Very Light
Current CAFÉ Standards								
CO2 Emissions								
Million MT/y	6%	7%	6%	6%	5%	7%	6%	5%
Metric tons/b crude	1%	1%	1%	1%	1%	2%	2%	1%
Energy Use								
Quadrillion Btu/y	5%	7%	6%	6%	5%	7%	5%	5%
Million Btu/b crude	0%	2%	1%	1%	0%	2%	1%	0%
New CAFÉ Standards								
CO2 Emissions								
Million MT/y	-	-	-	-	-	-	-	-
Metric tons/b crude	-	-	-	-	-	-	-	-
Energy Use								
Quadrillion Btu/y	-	-	-	-	-	-	-	-
Million Btu/b crude	-	-	-	-	-	-	-	-
Low Biodiesel Volume								
CO2 Emissions								
Million MT/y	0%	1%	1%	0%	0%	0%	0%	0%
Metric tons/b crude	-1%	0%	0%	-1%	-1%	-1%	-1%	-1%
Energy Use								
Quadrillion Btu/y	0%	1%	1%	0%	0%	0%	0%	0%
Million Btu/b crude	-1%	0%	0%	-1%	-1%	-1%	-1%	-1%
Partial E30								
CO2 Emissions								
Million MT/y	-3%	-2%	-3%	-3%	-3%	-3%	-3%	-2%
Metric tons/b crude	-2%	-1%	-1%	-2%	-2%	-2%	-1%	-1%
Energy Use								
Quadrillion Btu/y	-3%	-1%	-2%	-2%	-3%	-2%	-2%	-2%
Million Btu/b crude	-2%	0%	-1%	-1%	-1%	-1%	-1%	-1%
Full E30								
CO2 Emissions								
Million MT/y	-12%	-10%	-12%	-13%	-13%	-11%	-8%	-7%
Metric tons/b crude	-8%	-5%	-7%	-8%	-8%	-7%	-4%	-3%
Energy Use								
Quadrillion Btu/y	-10%	-9%	-10%	-11%	-10%	-9%	-9%	-9%
Million Btu/b crude	-5%	-4%	-5%	-6%	-6%	-5%	-5%	-5%
Sensitivity Cases								
High Biojet								
CO2 Emissions								
Million MT/y	-2%	-2%	-2%	-1%	-2%	-1%	-2%	-2%
Metric tons/b crude	2%	1%	2%	2%	2%	2%	1%	1%
Energy Use								
Quadrillion Btu/y	-2%	-2%	-2%	-1%	-2%	-1%	-3%	-2%
Million Btu/b crude	1%	1%	2%	2%	1%	2%	0%	0%
No Petroleum Coke								
CO2 Emissions								
Million MT/y	17%	19%	22%	21%	17%	18%	14%	12%
Metric tons/b crude	24%	30%	34%	31%	25%	25%	19%	15%
Energy Use								
Quadrillion Btu/y	13%	15%	17%	16%	13%	14%	10%	8%
Million Btu/b crude	20%	26%	28%	26%	19%	20%	15%	12%

Exhibit 16: Summary of CO2 Emissions per Crude Oil Input, by Crude Oil Slate and Product Slate

Product Slate & CO2 Emissions per Crude Oil Input	Crude Slate							
	Base	Ext. Heavy	Very Heavy	Heavy	Mid Expan	Import Indep	Light	Very Light
Current CAFÉ Standards								
Metric Tons/Barrel	0.044	0.050	0.048	0.046	0.044	0.044	0.041	0.040
Grams/Megajoule	7.0	7.9	7.6	7.4	7.1	7.2	6.6	6.5
New CAFÉ Standards								
Metric Tons/Barrel	0.043	0.049	0.047	0.046	0.044	0.043	0.040	0.040
Grams/Megajoule	7.0	7.8	7.5	7.3	7.1	7.0	6.5	6.5
Low Biodiesel Volume								
Metric Tons/Barrel	0.043	0.049	0.047	0.045	0.043	0.043	0.040	0.039
Grams/Megajoule	6.9	7.8	7.5	7.3	7.0	7.0	6.5	6.4
Partial E30								
Metric Tons/Barrel	0.042	0.049	0.046	0.045	0.043	0.043	0.039	0.039
Grams/Megajoule	6.8	7.7	7.4	7.2	6.9	6.9	6.4	6.4
Full E30								
Metric Tons/Barrel	0.040	0.047	0.044	0.042	0.040	0.041	0.038	0.038
Grams/Megajoule	6.4	7.4	7.0	6.7	6.5	6.6	6.3	6.3
Sensitivity Cases								
High Biojet								
Metric Tons/Barrel	0.044	0.050	0.048	0.047	0.044	0.044	0.040	0.040
Grams/Megajoule	7.1	7.8	7.6	7.5	7.2	7.2	6.6	6.6
No Petroleum Coke								
Metric Tons/Barrel	0.054	0.064	0.063	0.060	0.055	0.054	0.048	0.045
Grams/Megajoule	8.7	10.1	10.0	9.6	8.8	8.8	7.8	7.5

Exhibit 17: Refinery Modeling Results for U.S. Estimated Investments in Refining Capacity, by Crude Slate and Product Slate Billion Dollars

	Crude Slate							
Product Slate	**Base**	**Ext. Heavy**	**Very Heavy**	**Heavy**	**Mid Expan**	**Import Indep**	**Light**	**Very Light**
Current CAFÉ Standards	14	57	46	31	18	20	9	7
New CAFÉ Standards	16	49	38	29	19	20	12	12
Low Biodiesel Volume	16	50	39	29	19	20	12	12
Partial E30	15	47	36	26	19	19	13	13
Full E30	26	43	44	38	30	32	19	20
Sensitivity Cases								
High Biojet	13	45	36	27	18	19	9	9
No Petroleum Coke								
Low	80	120	120	100	80	80	60	50
High	140	200	210	190	140	130	100	90

Note: In 2011 dollars