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Crude Oil Investing in a Carbon Constrained World: 2017 Update

Jackie Forrest and Marcus Rocque

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Executive Summary

Since its publication in February 2016, investors have used the ARC Method to understand how their crude oil assets compare to others on a carbon intensity basis and to quantify the cost of future policy on their investment returns. In the absence of a method for measuring greenhouse gas ("GHG") emissions, investors in crude oil assets are largely unaware of the financial costs they face if more stringent climate change policies are introduced.

This update to the original ARC Method expands the list of available benchmark crude oils and incorporates new data and models. The list of benchmark crude oils has been expanded from 33 to 75, including estimates for US onshore plays like the Bakken and Eagle Ford. The updated ARC Method also incorporates new data and models, and updates the baseline for the US Refined Average from 2005 to 2014.

Using the ARC Method, investors can identify crude oil assets that can make attractive returns under a realistic range of carbon prices, while avoiding higher carbon assets that are more challenged by carbon levies. Because of the risk of more stringent GHG policy, some organizations, agencies, and individuals are suggesting that crude oil investors are being exposed to excessive financial risks. This is not always the case. Crude oils are not all equal in their carbon intensity. In the future, producers with lower carbon emissions could realize positive benefits compared to their higher carbon peers, such as higher demand for their products, lower energy use, and reduced operating and carbon compliance costs.

Beyond the benefits of using the ARC Method to understand and quantify investment risk, there are additional benefits from understanding GHG intensity for crude oil investing. By gathering data and modelling the GHG intensity of a crude oil operation, an investor can gain a greater awareness of the characteristics that lead to higher GHG intensity. Awareness of these dynamics should lead to better decisions on future investments; either by avoiding assets that are more challenged, or by making decisions early in a project's design that reduce the GHG intensity for relatively low cost (compared to making a change later in a project's life).

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About the ARC Energy Research Institute

Based in Calgary, Canada, the ARC Energy Research Institute conducts economic and investment analysis for ARC Financial Corp. and its stakeholders. ARC Financial Corp. is Canada's largest energy focused private equity manager specializing in the Canadian energy industry.

The ARC Energy Research Institute is dedicated to researching complex, interrelated trends that influence the energy business, including financial, political, environmental, technological, social and economic forces. All these elements of change will shape the future of the world's energy supply and its consumption.

Our unique approach to researching, collaborating and communicating allows us to continue our history of helping decision-makers demystify the complexities of energy systems. Our specialty is assessing risk and return during times of change and transition. Our ultimate pursuit is aggregating knowledge for the purpose of objective judgment.

Crude Oil Investing in a Carbon Constrained World: 2017 Update

Introduction

This report is a newly updated version of our original report "Crude Oil Investing in a Carbon Constrained World" that was published in February 2016. Since its original publication, investors have used the ARC Method to understand how their crude oil assets compare to others on a carbon intensity basis and to quantify the potential costs of future GHG policy on their returns.

This 2017 update to the ARC Method refreshes the original publication; expands the list of available benchmark crude oils from 33 to 75; incorporates new data and model versions; and updates the baseline for the average crude oil refined in the US from 2005 to the most recent 2014 data.

The pace and stringency of future GHG policy is still uncertain. However, this ambiguity has not changed the sentiment of investors who continue to ask corporations for greater transparency on climate change related financial risk. Public oil and gas producers are responding to shareholder requests for disclosure of the financial implications of a lower carbon world. [1] In June 2017, the United Nations ("UN") G20 Task Force [2] released its voluntary financial reporting rules for corporations to communicate climate change risks to shareholders.

Because of the concerns related to GHG emissions, some organizations, agencies, and individuals are suggesting that fossil fuel investors are being exposed to excessive financial risks, and that divestment is the only option to mitigate risk. We suggest this is not the case. What can be measured can be managed, especially in the case of GHG emissions.

In fact, not all impacts of potential carbon policy are negative to fossil fuel producers and their investors. Lower carbon producers could be provided a competitive advantage in a carbon constrained world. Compared to their higher carbon peers, lower carbon producers can realize positive benefits from stricter GHG policy, such as higher demand for their products, lower energy use, and relatively lower operating and carbon compliance costs.

The purpose of the ARC Method is to provide investors (banks, hedge funds, investment advisors, private equity, endowments, pension funds, etc.) with the analytic tools needed for estimating the GHG emissions of any crude oil asset. Properly interpreted, information generated from the ARC Method can allow investors to rationally assess the viability of their crude oil investments in a world with more stringent climate change regulations.

1. In 2015, BP and Shell were requested to disclose more information on climate risk through shareholder resolutions. In 2017, Shell committed to support recommendations by the Task Force on Climate Related Financal Dislocsures ("TCFD"). Through 2016 and into 2017 some more examples of shareholders asking for greater climate risk disclosure include: Suncor Energy, Cenovus, Exxon, Chevron and Occidental. Beyond oil and producers, Pennsylvania utility PPL Corp. - an electric power provider with coal generators - was also asked to disclose financial impacts from climate change policy.
2. During the 21st UN Climate Conference in Paris in November 2015, the Financial Stability Board (a group that reports to the G20) created a taskforce to develop climate risk disclosures. The group issued draft recommendations in December 2016, with final recommendations released in June 2017.

While there are a range of methods that could be employed for measuring and comparing the GHG emissions from crude oil assets, the advantage of the ARC Method is that it uses publicly available, transparent, and accredited models that are relatively easy to use.

There are four sections in the main body of this report: (1) An Introduction to GHG Emissions Life Cycle Analysis; (2) Basic Concepts in Measuring GHG Emissions for Crude Oil and the ARC Method; (3) Assessing the GHG Emissions and Investment Risk of a Specific Crude Oil Investment; and (4) the Conclusion.

The Appendix of this report provides detailed guidance on how to estimate the GHG emissions for crude oil assets, including a hands-on example of how to use the ARC Method to analyze a specific crude oil investment decision.

Finally, readers may be wondering why the ARC Method is limited to crude oil investing and does not cover other fossil fuels such as natural gas or coal. Compared with crude oil, the body of research and tools for estimating the relative GHG intensity of other fossil fuels is less evolved at this time. However, there is a considerable amount of academic and industry research currently underway and it is possible that similar tools and methods could become available for other fossil fuels in the future.

Organizations that Participated in a Review of this Report

Prior to publication, a draft version of this report was reviewed by both experts in the field of GHG emissions analysis and crude oil investors. The feedback from these participants was invaluable and helped shape the final version. Participation by an organization does not mean endorsement of the paper, however, ARC would like to acknowledge and thank the following organizations for their contribution to the report:

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Section 1: An Introduction to GHG Emissions Life Cycle Analysis

What is GHG Emissions Life Cycle Analysis?

"Cradle to grave" is a common term to describe processes from start to finish. In the world of energy systems, the equivalent term is "life cycle."

For example, the life cycle of a tonne of coal starts at a mine and can end at the light you see from a bulb in your house. All the processes and conversions that occur in-between – transporting the coal, burning it in a power plant, generating the electricity, transmitting it through the wires to your wall plug, and up to your lamp – are part of that life cycle. A specific beginning-to-end life cycle, such as the coal mine to light bulb, is termed a "pathway."

Energy life cycles provide a basis for measuring and comparing the various ways that society sources and uses its energy. For the purposes of this paper, we are interested in the amount of GHGs that are emitted into the atmosphere at every stage of an energy pathway – from production, to energy conversions, to delivery, and to end use.

GHG life cycle analysis ("LCA") is an established method that seeks to quantify all of the GHG emissions associated with each stage of the life cycle of a primary fuel such as oil or natural gas, along an explicit pathway. The analysis can provide information about an entire pathway, or partial segments in-between. LCA can also be used to compare the GHG emissions among fuels. For instance, it can compare the total GHG emissions for turning a car's wheels using either electricity or gasoline.

When LCA is undertaken for crude oil, the accounting considers all of the detailed stage-by-stage GHG emissions, from drilling and production through to the final use of petroleum fuels such as gasoline or jet fuel in an engine. There are upstream emissions associated with the exploration and production of crude oil from a well, and there are emissions released into the atmosphere when the oil is piped to a refinery. Refining the oil into gasoline and other products sends emissions up the stacks, and there are also emissions when the tanker truck delivers the gasoline to a retail station. Finally, the bulk of the emissions come from combusting the petroleum fuel in the engine of a car, airplane or ship. For crude oil, we refer to this full-cycle pathway of GHG emissions as "well-to-combustion."

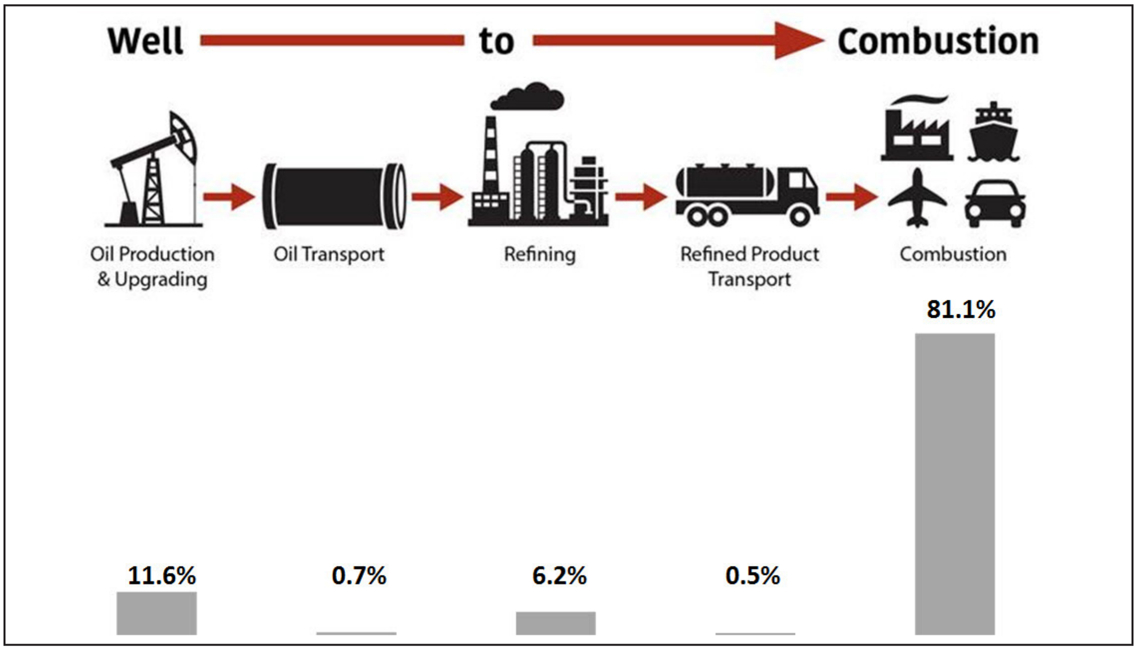
The results of an LCA can vary significantly among crude oil sources. Production practices drive different levels of oil production emissions, heavier oils require more GHG emissions for refining, and each crude oil yields a different slate of refined products, causing differences in the amount of combustion emissions.

This method of differentiating between various crude oil sources using LCA is well accepted and is commonly used in government policies. In fact, such granular emissions analysis is already the basis for existing policies including the Environmental Protection Agency's ("EPA") Renewable Fuel Standard, California's Low Carbon Fuel Standard and the European Union's Fuel Quality Directive.

Figure 1 shows the percentage breakdown of the well-to-combustion emissions for the average crude oil refined in the US ("US Refined Average (2014)"), from production through to combustion. Five broad stages are considered across this generalized pathway: (1) oil production and upgrading;[3] (2) oil transportation to a

3. Upgrading is when very heavy crude oils are partially refined into lighter crude oils.

Figure 1: Estimated Well-to-Combustion GHG Emissions from Crude Oil*



Source: ARC Energy Research Institute, using input data from the US Department of Energy National Energy Technology Laboratory to define the US Refined Average (2014)
*US Refined Average (2014)

refinery; (3) refining; (4) refined product transportation to the end user; and (5) combustion of the petroleum fuel in a car, airplane, power plant or ship. Combustion of refined products by the final consumer generates the majority of the GHG emissions across the crude oil life cycle, at 81.1 percent. Meanwhile, on average, the upstream activities that a producer of crude oil is responsible for constitute 11.6 percent of all the well-to-combustion emissions.

Why is GHG LCA Appropriate for Considering Investment in Assets that Produce Hydrocarbons?

Fossil fuel producers operate at the front end of the well-to-combustion pathway. Many of these companies are coming under increasing scrutiny for their segment's contribution to GHG emissions and the related climate change effects.

For crude oil producers, a GHG policy imposed by government could act to increase their extraction costs directly. Producers are also exposed to indirect impacts if extra costs are imposed further down the life cycle, as they could increase the costs for refining crude oil, or boost the retail price of petroleum fuels, such as gasoline. By adding costs across the oil life cycle, GHG policy intends to lessen consumer demand for petroleum fuels; encouraging greater efficiency and lower carbon alternatives.

Although meaningful carbon policy has not yet been implemented broadly, some financial institutions are being challenged to divest of all their hydrocarbon assets, or at least the assets that are perceived to originate from the more carbon intense pathways, such as heavier crude oils or coal. The objective of such divestment is a means to financially sanction all, or part of the hydrocarbon industry, effectively raising its cost of capital.

Since the consumer's end use drives the majority of the GHG emissions from hydrocarbons, the effectiveness of an upstream-only mitigation strategy remains open to debate, as higher production costs (either through a carbon fee on production, or by applying a higher cost of capital for producers), may not materially change how many hydrocarbons are ultimately combusted. Nevertheless, the trend of increasing carbon costs for hydrocarbon producers is an important one to watch, and necessitates better measurement of GHG emissions across all carbon pathways, including for crude oil.

Proper, consistent, and comprehensive reporting of LCA emissions is necessary for assessing risk as it pertains to investment decisions. Context is also vital. Full LCA reporting allows the investor to estimate the GHG emissions generated by a specific investment, and how they compare to the emissions from other investment opportunities. From a financial perspective, the data generated from this type of exercise enables an investor to consider the range of potential carbon costs that may impact their portfolio of hydrocarbon investments in the future.

Section 2 : Basic Concepts in Measuring GHG Emissions for Crude Oil and the ARC Method

A number of governments already use crude oil LCA as a basis for their GHG policies. In order to develop these policies, numerous studies have been published on the topic, from academic papers, to studies published by consultants and government agencies. Most often, past research has been technical in nature, providing answers to specific policy questions. What makes this paper unique is that it outlines a straightforward method for measuring GHG intensity using publicly available models, providing the investor with a tool for completing their own assessment of the GHG emission investment risk associated with a particular crude oil asset.

The following section outlines some basic LCA concepts and some introductory information on how GHG emissions are measured. For more detailed guidance, please refer to the Appendix of this report, which includes a sample calculation.

Challenges in Measuring Life Cycle GHG Emissions for Crude Oil

To measure the GHG emissions from a specific crude oil, data must be collected and the user must make numerous decisions about what emissions to include. Depending on the purpose of the study, different levels of measurement and scope are applied. Because of differences in scope and methodology, it is improper to directly compare GHG emissions estimates across various studies. This would be the equivalent of comparing "apples to oranges." When using the ARC Method however, an investor can compare their project of interest on an "apples-to-apples" basis with a group of other benchmark crude oils that are included in this report. The following section outlines some of the key drivers that led to different results between studies, along with details on the ARC Method's approach in regards to handling each of the issues: [4]

1. Data Issues

Collecting data that describes the production characteristics of crude oil can be a challenge. It is especially difficult in international jurisdictions that do not require oil and natural gas data to be made publicly available.

4. The issues that are outlined within this paper have all been well documented in other reports, including: Jackie Forrest, Cheryl Dereniwski, and Kevin Birn's, "Comparing the GHG Intensity of the Oil Sands and the Average US Crude Oil," *IHS Energy Special Report,* (May 2014).

For regions with limited, non-transparent data, defaults or best estimates are commonly used in place of collected data. When working with a more limited data set, the margin of error associated with the estimate is greater.[5]

This report includes GHG emissions estimates for 75 crude oils using the ARC Method. These benchmark crude oils provide an investor with some context as to how the GHG intensity of their specific investment compares to others. All of the estimates provided rely on publicly available data for characterizing the crude oils. While data on North American crude oils is relatively transparent, in general, estimates for international crude oils rely on much less precise information.

2. Different Boundaries for Measurements

Some studies only measure the GHG emissions that are directly emitted from the oil and natural gas production site or oil refinery, whereas other studies choose to consider the full range of emissions, including upstream impacts. These upstream impacts would include factors such as the carbon dioxide ("CO_2") that is released when electricity is generated at an off-site power plant.

Some studies also account for the emissions impacts from land use change. The logic behind this is that prior to the development of an oil field, vegetation has generally accumulated and is storing carbon on the land. When an oil production facility is built, the vegetation is removed and this reduces the land's ability to absorb carbon. Quantification of this GHG impact is referred to as land use change.

Depending on the purpose of the study, different boundaries are appropriate. In the ARC Method, a wide boundary is used for measuring GHG emissions, including: the direct on-site emissions; the upstream GHG emissions for producing and delivering fuels that are used to extract, refine, and transport the crude oil; and impacts from land use change. It is appropriate to measure GHG emissions with a wide boundary since this provides the most insight to the total GHG impact associated with developing crude oil assets.

3. Accounting for the By-Products of Crude Oil Extraction

When crude oil is extracted, by-products can be produced, such as natural gas, natural gas liquids ("NGLs") and electricity. In the case where natural gas is extracted as a by-product of oil, it offsets the need to produce natural gas elsewhere. The same holds for the production of electricity. When electricity is produced and exported as a by-product of oil production, it is reducing the need to generate power somewhere else. Because of this substitution effect, life cycle GHG studies often apply a credit for the by-products (since they reduce the amount of GHG emissions generated at another location). A different approach is to account for the energy content of all of the by-products, and to divide the total GHG emission for extraction among all of the products (both crude oil and by-products); this method is often called the "allocation method."

In the ARC Method, a credit is applied for the by-products. This is the most appropriate way to compare crude oils, and only crude oils, from the perspective of how much carbon they add to the atmosphere.

4. Accounting for Co-Products in Refining

Crude oil is refined into various products such as gasoline, diesel, aviation, and bunker fuel. Most crude oil LCA studies report their results on the basis of the fuels produced. For example, they publish the carbon intensity per unit of gasoline or diesel. To report on the

5. For more information on how the margin of error becomes greater when data is more limited, refer to Kourosh Vafi and Adam R. Brandt's report "Uncertainty of Oil Field GHG Emissions Resulting from Information Gaps: A Monte Carlo Approach," *Environmental Science and Technology* 48, no. 17 (2014): 10511- 10518.

final fuel basis, the studies must first calculate the total emissions for refining a barrel of oil, and then determine a method for dividing those among the final refined products (gasoline, diesel, etc). Studies differ widely in their method for allocating the emissions among fuels, and this is a major source of discrepancy when comparing results among studies.

Because the ARC Method is conducted from the perspective of a crude oil investor, and not an end consumer, the GHG emissions are reported on a per barrel of crude oil basis and not a final fuel basis. This is the most logical basis for evaluating an oil investment, and avoids the complications associated with allocating the GHG emissions to each petroleum fuel.

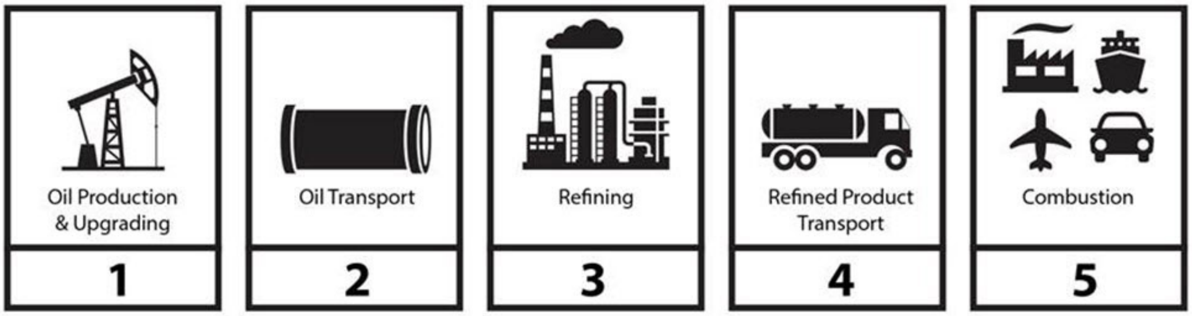
How to Measure the Life Cycle GHG Emissions from Crude Oil Using the ARC Method

The goal of this paper is to present a transparent, simple method for quantifying the GHG emissions from crude oil, for investors. To measure the life cycle GHG emissions for crude oil, sources of emissions are divided into five stages: (1) oil production and upgrading; (2) oil transportation to a refinery; (3) refining; (4) refined product transport to the end user; and (5) fuel combustion in a car, airplane, power plant or ship (see Figure 2). To measure the GHG emissions for each of these five well-to-combustion stages, the ARC Method draws on publicly available GHG estimation models and data. The following briefly outlines the ARC Method for calculating the GHG emissions for each stage; a more detailed explanation can be found in Section 1 of the Appendix.

1. Oil Production and Upgrading

Stanford University's Oil Production Greenhouse Gas Emissions Estimator ("OPGEE") is used in the ARC Method for estimating the GHG emissions from crude oil production. This Excel-based model is the basis of the crude oil GHG intensity values used in California's Low Carbon Fuel Standard program. The model is publicly available and can be downloaded at Stanford's website.[6] In our original report from February 2016, we used OPGEE version 1.1 Draft D. This updated version of the ARC Method uses version 1.1 Draft E.

Figure 2: The Five Stages of Well-to-Combustion GHG Emissions from Crude Oil



Source: ARC Energy Research Institute

6. To access OPGEE version 1.1 Draft E on the Stanford University website, please use the following link: https://eao.stanford.edu/research-areas/opgee
For more information on OPGEE refer to: Hassan M. El-Houjeiri, Adam R. Brandt, and James E. Duffy's report "Open-Source LCA Tool for Estimating Greenhouse Gas Emissions from Crude Oil Production Using Field Characteristics," *Environmental Science and Technology* 47, no. 11 (2013): 5998-6006.

The OPGEE model uses more than 50 data inputs to estimate the GHG emissions for producing and transporting crude oil. However, when less data is available, the model relies on pre-loaded defaults. Once the inputs to characterize the oil production are entered in OPGEE, it automatically estimates the GHG emissions for production and upgrading.

2. Oil Transport

The OPGEE model also estimates the emissions for moving the crude oil between the oil field and the refinery. To estimate these emissions, the model requires the distance that the oil is transported to the refinery and the mode of transportation that is used (i.e. pipeline or tanker).

In order to compare the life cycle GHG emissions intensity among different crude oils, the geographical location of the oil refinery must be the same. Therefore, the ARC Method assumes that the refinery's location is in Houston, Texas, as the Gulf Coast region is by far the largest single refining center in the United States. Crude oils that are further away from North America could be slightly disadvantaged by choosing Houston as their location, as they would end up having higher oil transport emissions than if a refinery location closer to the oil field were chosen. However, the refinery location assumption is not that significant to the final results, since the transportation of crude oil is a relatively small fraction of the total well-to-combustion emissions, typically being between 0.5 and 2.0 percent.

3. Refining

The University of Calgary's Petroleum Refinery Life Cycle Inventory Model ("PRELIM") is used for estimating the GHG emissions for crude oil refining. This Excel-based model is publicly available and can be downloaded at the University's website.[7] In our original report from February 2016, ARC used PRELIM version 1.0. The updated ARC Method uses version 1.1.

In the ARC Method for estimating the GHG emissions for crude oil, the PRELIM model serves two purposes. First, it estimates the GHG emissions for refining each crude oil stream, and second, it predicts the slate of petroleum fuels – gasoline, jet fuel, diesel, bunker fuel, and petroleum coke – that a refinery can make from each crude oil.

To estimate GHG emissions for refining, the PRELIM model requires a detailed profile of the crude oil called a "crude oil assay." The assay reports the volume and quality of the crude oil that is boiled-off in each temperature range. In the case that a crude oil assay is not available, the ARC Method uses an analog method for predicting the GHG emissions, whereby a pre-loaded crude oil with similar properties is selected. While using the actual crude oil assay is the most accurate method, the analog approach is the best available technique in many cases, especially since detailed data on the characteristics of some crude oils are not publicly available.

Refineries vary in their complexity, and by default, the PRELIM model will determine the appropriate refinery for each crude oil based on its characteristics.

4. Refined Product Transport

To estimate the emissions for transporting crude oil from the refinery to the retail station, the ARC Method uses research from the US Department of Energy National Energy Technology Laboratory ("DOE/NETL"). In a 2008 paper titled "Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions

7. The PRELIM model can be downloaded from the University of Calgary's website: http://www.ucalgary.ca/lcaost/prelim
This updated report uses version 1.1 of PRELIM.

of Petroleum-Based Fuels," DOE/NETL estimated the average GHG emissions for transporting refined products in the United States.[8] Using the DOE/NETL data, the ARC Method assumes that all refined products are transported by pipeline to the retail station with a carbon intensity of 2.39 kilograms of carbon dioxide equivalent per barrel ("kgCO_2e/barrel") of refined product transported. This number is used in conjunction with the PRELIM output describing the volume of each product produced at the refinery to determine the total emissions that are associated with transporting the refined products that are produced from each crude oil.

5. Combustion

The amount of GHG emissions from combusting a unit of fuel (gasoline, diesel, etc.) is a well-known physical property. Whether the gasoline is derived from a light African crude oil or a heavy Mexican crude oil, the combustion emissions are the same. This is because the refinery's objective is to make refined products that have similar chemical properties, no matter what oil feedstock is used. Table 1 outlines the GHG emissions factors for combusting each type of petroleum fuel. In the ARC Method, these factors are used in combination with the refined product output results from PRELIM to generate an estimate of total combustion emissions for a particular crude oil.

The ARC Method includes combustion emissions from liquid petroleum products only (i.e. motor gasoline, diesel fuel, etc.). The GHG emissions for burning solid petroleum coke, which is a by-product of refining heavy crude oils, are not included.

Excluding petroleum coke emissions is a common practice in LCA[9] comparisons because one of the common uses for petroleum coke is as a substitute for coal

Table 1: CO_2 Emissions Factors for Combusting Refined Products

	kgCO_2e/barrel of refined product
Motor Gasoline	370.3
Diesel Fuel	429.8
Jet Fuel	411.1
Bunker Fuel	452.9
Fuel Oil	462.1
Liquefied Petroleum Gas	239.7

Source: EPA 2014 Emissions Factors for GHG Inventories
(Diesel is the average of Distillate #1 and #2, Bunker is the average of Residual Fuel #5 and #6, Fuel Oil is Distillate #4).

in power generation. Since the combustion of petroleum coke to produce electricity offsets the need to combust a similar amount of coal, these emissions are not viewed to be material to the amount of GHG emissions emitted to the atmosphere.

This assumption only materially impacts heavy crude oils (since lighter crude oils do not produce much petroleum coke when refined). While it is not our assumption, if the combustion emissions from burning the petroleum coke produced at the refinery are included, this would increase the well-to-combustion GHG emissions for heavy oils in the range of 10 to 20 percent.

Section 3 : Assessing the GHG Emissions and Investment Risk of a Specific Crude Oil Asset

This section demonstrates how to use data from the ARC Method for evaluating investment decisions in two ways. The first method compares the GHG emissions from a particular crude oil to others, using the full well to combustion life cycle emissions for a benchmark

8. For estimates of the GHG emissions for transporting refined products to the retail station, see Table 5-10 on page 94 of: Timothy J. Skone and Kristin Gerdes', "Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels," *US Department of Energy National Energy Technology Laboratory,* (November 2008).
9. Organizations that have excluded the emissions for burning the petroleum coke that is produced at the refinery in their past crude oil LCA analysis include: IHS, Jacobs Consultancy (who only included the incremental emissions from substituting petroleum coke instead of coal for power generation in their results), TIAX, and DOE/NETL.

set of crude oils. This is useful since it helps illustrate the relative climate change impact of a crude oil and how it stacks-up to others when all the GHG emissions released to the atmosphere are accounted for. The second method calculates only the emissions that come directly from the producer's well site and operations. This portion of the emissions is used to calculate the producer's direct liability in the case of more stringent GHG policy.

Method 1: Comparing A Benchmark Set of Crude Oils on a Well-to-Combustion Basis

To enable investors to understand how the carbon intensity of a specific crude oil investment compares to others on well-to-combustion basis (and considering all GHG emissions emmited to the atmosphere), a benchmark set of crude oils has been created using the ARC Method. When using the ARC Method, an investor can compare the GHG emissions intensity of their specific investment to the data sets shown in Figure 3 and Table 2.

In this update to the ARC Method, the benchmark set now includes 75 crude oils that were modelled using input data from the Carnegie Endowment's Global Oil Climate Index ("OCI")[10] and an estimate for the US Refined Average (2014). The US average crude oil has been updated from 2005 (in our original report) to 2014 using input data from a 2016 paper released by DOE/NETL.[11] The methodology for calculating the 2014 benchmark is explained in detail in the Appendix of this report.

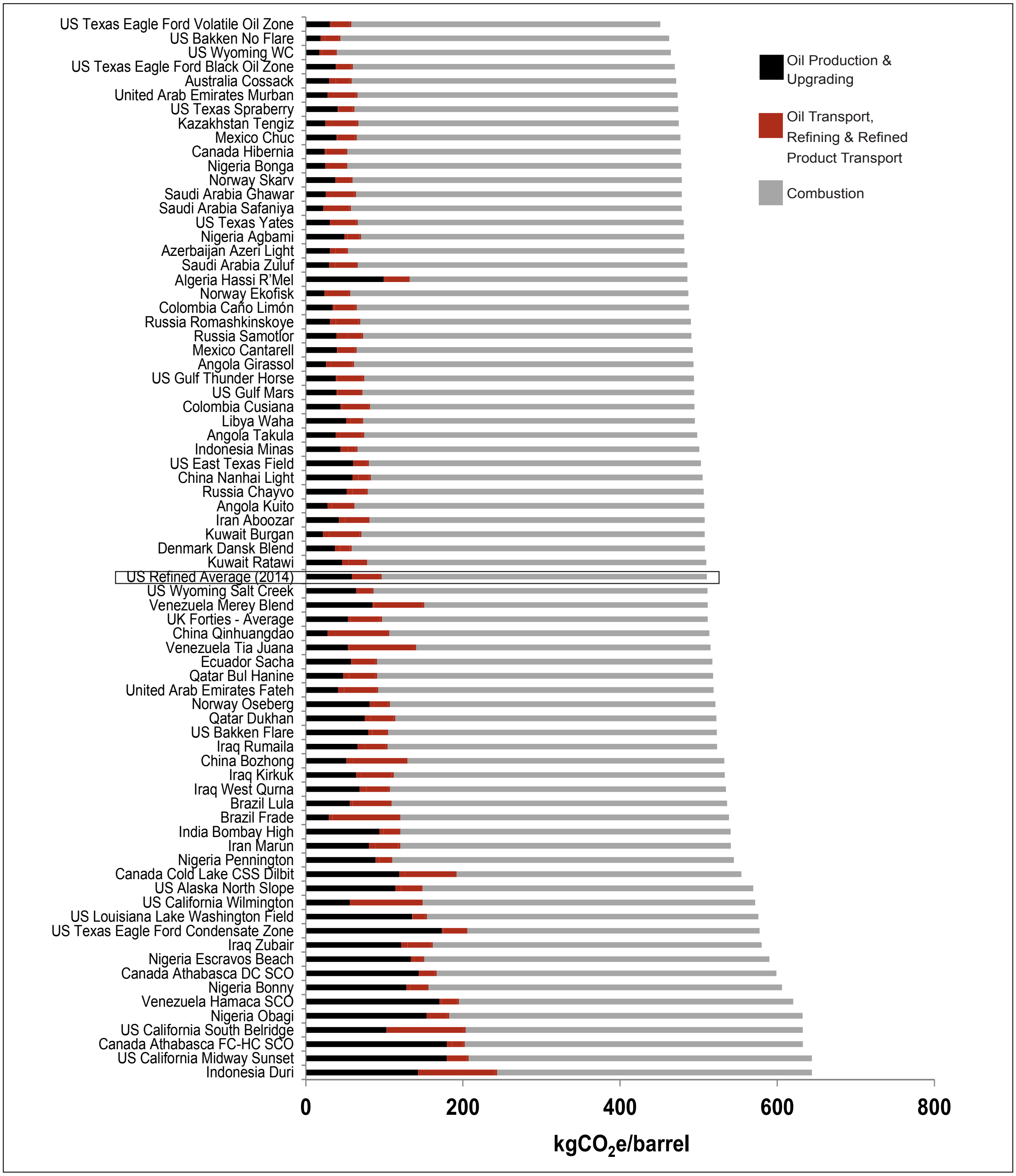
Method 2: Evaluating the Direct Emissions, to Estimate a Producer's Carbon Cost

Assuming that oil and gas production facilities need to pay for the carbon they emit, a carbon levy would apply to their direct GHG emissions only. As explained in the LCA method section previously, the production GHG emissions intensity in the LCA results includes the direct GHG emissions, but also includes the emissions that are generated off-site (for example, emissions for producing electricity at an off-site power plant), and a credit for any by-products (natural gas, electricity, or natural gas liquids) and land use. While, its is appropriate to include these indirect effects, for the purpose of LCA comparisons it is not reasonable to include them when calculating the direct carbon emissions that a producer would be responsible for.

The ARC Method outlines how to estimate the contribution from direct oil production emissions only. Once these direct production emissions are understood, the results must be further broken down into the portion of emissions coming from combustion and methane. Combustion emissions are the result of burning hydrocarbons and creating CO_2. Methane losses come from a variety of sources, including venting, fugitive leaks from equipment, and losses when flare stack combustion is incomplete. The separation is important because in some jurisdictions the carbon policy and cost differ for each source. The ARC Method for separating out the direct emissions, including breaking them into the combustion and methane, is discussed further in the Appendix in Section 3.

10. For data to describe the production practices for the 75 crude oils, see Excel input data from Deborah Gordon, Adam Brandt, Joule Bergerson, and Jonathan Koomey's, "Know Your Oil: Creating a Global Climate Index – Phase 2," *Carnegie Endowment for International Peace,* (2016). To access the Excel data sheet that describes the 75 crude oils production practices, visit the following website:
http://oci.carnegieendowment.org/assets/resources/opgee-oci-website-75-fields-v20.xlsx
See the Appendix, Section 1.1 for more details
11. Gregory Cooney, Matthew Jamieson, Joe Marriott, Joule Bergerson, Adam Brandt, and Timothy J. Skone, "Updating the U.S. Life Cycle GHG Petroleum Baseline to 2014 with Projections to 2040 Using Open-Source Engineering-Based Models," *Environmental Science and Technology in Association with the US Department of Energy National Energy Technology Laboratory,* (November 2016), 977-987.

Figure 3: Well-to-Combustion Estimated GHG Emissions for a Benchmark Set of Crude Oils



Source: ARC Energy Research Institute

Benchmark crude oils use input data from the Carnegie Endowment's Global Oil Climate Index and the US Department of Energy, National Energy Technology Laboratory

Table 2: Well-to-Combustion Estimated GHG Emissions for a Benchmark Set of Crude Oils

$kgCO_2e$/barrel	Oil Production and Upgrading	Oil Transport	Refining	Refined Product Transport	Combustion	Total: Well-to-Combustion	*Well-to-Combustion Percent Difference to the US Refined Average (2014)*	*Oil Production and Upgrading Percent Difference to the US Refined Average (2014)*
Indonesia Duri	143	11	87	2	401	**644**	*26%*	*142%*
US California Midway Sunset	179	0	25	2	437	**644**	*26%*	*204%*
Canada Athabasca FC-HC SCO	179	7	14	2	430	**633**	*24%*	*204%*
US California South Belridge	103	0	98	3	429	**633**	*24%*	*74%*
Nigeria Obagi	154	5	21	3	450	**632**	*24%*	*161%*
Venezuela Hamaca SCO	170	2	20	3	425	**620**	*22%*	*189%*
Nigeria Bonny	128	5	21	3	450	**606**	*19%*	*117%*
Canada Athabasca DC SCO	144	7	14	2	432	**599**	*17%*	*144%*
Nigeria Escravos Beach	134	5	10	2	439	**590**	*16%*	*127%*
Iraq Zubair	122	8	30	2	419	**580**	*14%*	*106%*
US Texas Eagle Ford Condensate Zone	173	2	28	2	372	**577**	*13%*	*194%*
US Louisiana Lake Washington Field	135	1	16	2	422	**576**	*13%*	*130%*
US California Wilmington	56	0	90	3	423	**572**	*12%*	*-5%*
US Alaska North Slope	114	7	25	2	421	**570**	*12%*	*93%*
Canada Cold Lake CSS Dilbit	119	7	64	2	362	**554**	*9%*	*102%*
Nigeria Pennington	89	5	14	2	435	**545**	*7%*	*51%*
Iran Marun	80	8	29	2	421	**541**	*6%*	*36%*
India Bombay High	94	5	19	2	420	**541**	*6%*	*59%*
Brazil Frade	30	5	84	3	418	**538**	*5%*	*-50%*
Brazil Lula	56	4	47	3	427	**536**	*5%*	*-5%*
Iraq West Qurna	69	8	28	2	427	**535**	*5%*	*16%*
Iraq Kirkuk	64	7	39	3	421	**533**	*4%*	*9%*
China Bozhong	52	9	67	2	403	**533**	*4%*	*-12%*
Iraq Rumaila	66	9	27	2	419	**523**	*3%*	*12%*
US Bakken Flare	80	5	18	2	418	**523**	*2%*	*35%*
Qatar Dukhan	75	7	29	2	409	**523**	*2%*	*28%*
Norway Oseberg	81	5	18	2	414	**521**	*2%*	*38%*
United Arab Emirates Fateh	41	8	41	3	427	**519**	*2%*	*-30%*
Qatar Bul Hanine	48	8	33	2	427	**518**	*2%*	*-19%*
Ecuador Sacha	58	3	28	2	427	**517**	*1%*	*-2%*
Venezuela Tia Juana	54	2	83	2	375	**515**	*1%*	*-9%*
China Qinhuangdao	28	9	67	2	407	**514**	*1%*	*-53%*
UK Forties - Average	54	3	37	2	415	**512**	*0%*	*-9%*
Venezuela Merey Blend	85	2	62	2	361	**512**	*0%*	*43%*
US Wyoming Salt Creek	64	4	16	2	425	**511**	*0%*	*9%*
US Refined Average (2014)	**59**	**4**	**32**	**2**	**414**	**510**	*0%*	*0%*
Kuwait Ratawi	46	8	21	2	432	**510**	*0%*	*-21%*
Denmark Dansk Blend	37	6	13	3	449	**508**	*0%*	*-37%*
Kuwait Burgan	22	8	39	3	436	**508**	*-1%*	*-63%*
Iran Aboozar	42	8	28	2	426	**508**	*-1%*	*-28%*
Angola Kuito	28	6	26	3	445	**507**	*-1%*	*-53%*
Russia Chayvo	52	7	17	2	427	**506**	*-1%*	*-11%*
China Nanhai Light	60	8	13	2	422	**505**	*-1%*	*1%*
US East Texas Field	60	1	17	2	423	**503**	*-1%*	*3%*
Indonesia Minas	44	10	10	2	435	**501**	*-2%*	*-25%*
Angola Takula	38	5	29	2	424	**498**	*-2%*	*-36%*
Libya Waha	51	6	14	2	422	**495**	*-3%*	*-13%*
Colombia Cusiana	44	2	33	2	413	**495**	*-3%*	*-26%*
US Gulf Mars	39	1	29	2	422	**494**	*-3%*	*-33%*
US Gulf Thunder Horse	38	1	33	2	419	**494**	*-3%*	*-35%*
Angola Girassol	26	5	28	3	432	**493**	*-3%*	*-56%*
Mexico Cantarell	40	1	22	2	428	**493**	*-3%*	*-33%*
Russia Samotlor	39	15	16	2	418	**491**	*-4%*	*-34%*
Russia Romashkinskoye	31	7	29	2	421	**490**	*-4%*	*-47%*
Colombia Caño Limón	34	3	26	2	423	**488**	*-4%*	*-42%*
Norway Ekofisk	24	4	27	2	430	**487**	*-5%*	*-60%*
Algeria Hassi R'Mel	99	4	26	2	354	**486**	*-5%*	*68%*
Saudi Arabia Zuluf	30	8	26	2	419	**486**	*-5%*	*-50%*
Azerbaijan Azeri Light	31	7	14	2	428	**482**	*-6%*	*-47%*
Nigeria Agbami	49	4	15	2	411	**482**	*-6%*	*-17%*
US Texas Yates	31	1	32	2	415	**481**	*-6%*	*-48%*
Saudi Arabia Safaniya	22	8	25	2	421	**479**	*-6%*	*-62%*
Saudi Arabia Ghawar	26	8	28	2	415	**479**	*-6%*	*-57%*
Norway Skarv	38	3	16	2	419	**479**	*-6%*	*-36%*
Nigeria Bonga	25	5	21	3	425	**478**	*-6%*	*-58%*
Canada Hibernia	24	2	25	2	424	**477**	*-6%*	*-59%*
Mexico Chuc	39	1	23	2	411	**477**	*-7%*	*-33%*
Kazakhstan Tengiz	25	10	30	2	408	**475**	*-7%*	*-58%*
US Texas Spraberry	41	1	18	2	412	**474**	*-7%*	*-31%*
United Arab Emirates Murban	28	8	28	2	407	**473**	*-7%*	*-53%*
Australia Cossack	30	9	18	2	413	**471**	*-8%*	*-49%*
US Texas Eagle Ford Black Oil Zone	38	2	17	2	409	**470**	*-8%*	*-35%*
US Wyoming WC	18	3	16	2	425	**464**	*-9%*	*-70%*
US Bakken No Flare	19	5	18	2	418	**463**	*-9%*	*-68%*
US Texas Eagle Ford Volatile Oil Zone	31	2	23	2	393	**451**	*-12%*	*-48%*

Source: ARC Energy Research Institute

Benchmark crude oils use input data from the Carnegie Endowment's Global Oil Climate Index and the US Department of Energy, National Energy Technology Laboratory

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Once it has been determined how many emissions are caused by combustion and methane per barrel of oil produced, the carbon intensity values are used to estimate the cost of carbon policy under a range of possible levies on CO_2 and methane (see text box "What is a Realistic Range to Consider for Future Carbon Pricing?"). The additional costs due to carbon pricing can then be included in financial models to understand the sensitivity of investment returns to various levels of carbon cost.

Besides levies on direct emissions, the investor could also try to include the indirect carbon costs in their financial models. For instance, if a power plant has to pay a carbon levy, then the price of electrical power for the oil producer may increase. An investor could account for this higher cost in their return calculations. Similarly, if a crude oil refiner is burdened with a carbon levy, they may be unwilling or unable to pay the same price as before for the raw oil, especially for a crude oil that has higher-than-average GHG emissions for refining. In this case, an investor may want to account for a crude oil discount in their investment decision. However, some caution is warranted when accounting for these indirect effects as market dynamics are complicated, and exactly how the burden of a carbon levy on a refinery or a power plant would be shared between consumers and producers is uncertain.

In a world with a price on carbon, an investor might assume that lower carbon crude oil investments will always fare better than higher carbon investments. However, since carbon costs are only one factor among many impacting financial returns, there are exceptions. Projects with superior assets and margins will fare best in a carbon constrained world, even if they happen to be investments with higher carbon intensities.

What is a Realistic Range to Consider for Future Carbon Pricing?

Future carbon policy could take many forms, from rules that require operators to replace specific equipment to a price for emitting CO_2. Whichever method is used, GHG policy will increase production costs. Since it is impossible to predict how policy will evolve in the many countries where crude oil is produced and consumed, the simplest method is to use a carbon price as a proxy of how costs could increase with more stringent GHG policy. Appropriate price estimates must be selected for both CO_2 and methane.

One perspective on future carbon pricing can be found in the International Energy Agency's ("IEA") *World Energy Outlook* from 2016 which includes a number of future carbon policy scenarios. In their reference case called the "New Policy Scenario," they assume carbon taxes reach around $US 20/tonne of CO_2e in 2020 and rise to $US 40/tonne of CO_2e by 2030. The IEA's 450 ppm scenario assumes aggressive actions are taken to limit global GHG emissions in the Earth's atmosphere to 450 parts per million (a level that is predicted to limit global warming to two degrees Celsius). In this case, carbon taxes are assumed to reach around $US 100/tonne by 2030 and $US 140/tonne by 2040.

Investors will have to be aware of policy developments in the regions in which they operate, as the pace of carbon policy implementation around the world will vary greatly. Some jurisdictions like Canada and Europe have already begun to impose carbon costs, while other regions could resist implementing carbon policy for years to come.

To understand how to use the carbon intensity information for evaluating an investment, see the text box "Using the ARC Method to Evaluate a Crude Oil Investment Decision."

Section 4: Conclusion

Investors in crude oil assets are largely unaware of how to monitor, analyze, report and assess risks associated with holding carbon assets in their portfolios. This has led to concerns about investing in oil and gas, especially considering that climate change mitigation efforts could result in more stringent government policies over time. Because of this dynamic, some organizations are suggesting that crude oil investors are exposed to excessive financial risks, and that divestment is the only option to mitigate risk. We suggest that this is not the case. Using the proposed methods contained within this report, investors can identify crude oil assets that can continue to make attractive returns under a realistic range of carbon prices over many decades.

Beyond the benefits of using the ARC Method to understand and quantify investment risk, we have found additional benefits from this work by understanding the GHG emissions from our existing investment portfolio. By gathering data about our investments and modelling the GHG intensity, we have gained a greater awareness of the characteristics that lead to higher GHG intensity operations. Awareness of these dynamics will lead to better decisions about future investments, either by avoiding more challenged assets or by making decisions early in a facility's design that can reduce the GHG intensity at a relatively low cost (compared to making a change later in a project's life).

With this updated version of the ARC Method, the goal is to add to the existing body of work on the topic, and provide investors with the most current information and methods for quantifying the GHG emissions from crude oil assets. The tools within offer a consistent protocol for assessing, reporting, and comparing the GHG intensity of their crude oil investments on the basis of GHG intensity. Properly interpreted, data derived from the ARC Method allows investors to quantitatively and rationally make investment decisions about oil investments in a carbon constrained world.

Using the ARC Method to Evaluate a Crude Oil Investment Decision

Bob's investment portfolio has two existing crude oil investments, Asset A and Asset B. Using the ARC Method, Bob has estimated the well-to-combustion GHG intensity for each of his existing oil fields and the direct emissions from his oil field production sites (see Table 2). Currently, there is no charge for emitting carbon from his oil fields. However, Bob believes that a $40/tonne of CO2e charge could be introduced in the coming years and this would increase his production cost by $1.26/barrel on average. Adding this extra cost to his financial models, Bob determines that the average internal rate of return ("IRR") for his two investments would decrease by 3.6 percent if the carbon fee were introduced.

Bob is now evaluating a new investment. The oil field looks like a profitable venture, but Bob is concerned about its higher GHG intensity. The oil field has direct, on-site production emissions that are 50 percent higher than Bob's existing crude oil assets. Yet, despite the higher carbon intensity, Bob finds that a $40/tonne of CO2e levy only reduces his investment returns by 4.0 percent — a similar level to his existing portfolio. The higher margins of this new asset allow it to absorb the extra carbon cost without greatly impacting the investment returns. Bob now has the data he needs to make an informed decision on whether or not to invest in the new higher carbon, oil production asset.

Table 3: Bob's Investment Portfolio GHG Emissions and Return Data

	Well-to-Combustion		Direct, On-Site Production		
	(kgCO_2e/barrel)	Difference From US Refined Average (2014)	Direct, On-Site Production Emissions (kgCO_2e/barrel)	Extra Production Costs From $40/Tonne of CO_2e Carbon Fee	Change to IRR With $40/Tonne of CO_2e Carbon Fee
Asset A	473.0	-7%	29.0	$1.16/barrel	-3.2%
Asset B	505.0	-1%	34.0	$1.36/barrel	-3.9%
Average for Bob's Investment Portfolio (Asset A and B)	**489.0**	**-4%**	**31.5**	**$1.26/barrel**	**-3.6%**
New Asset	566.0	11%	47.0	$1.88/barrel	-4.0%
Average for Bob's Investment Portfolio with New Asset	**515.0**	**1%**	**37.0**	**$1.48/barrel**	**-3.7%**

Source: ARC Energy Research Institute

Appendix

This Appendix includes three main sections. The first section provides an overview of the method that was used (the "ARC Method") to generate the greenhouse gas ("GHG") emissions measurements for a benchmark set of crude oils. This includes two subsections: (1) the estimates that used input data from the Global Oil-Climate Index ("OCI"); and (2) the estimate of the average US crude oil baseline ("US Refined Average (2014)"), which used input data from the US Department of Energy National Energy Technology Laboratory ("DOE/NETL"). The second section provides guidance on how to use the ARC Method for informing investment decisions, and the third section provides readers with a step-by-step example of how to evaluate the GHG emissions intensity, and estimate a potential range of carbon costs for a hypothetical crude oil investment.

Section 1: Generating Life Cycle GHG Emissions Estimates for ARC's Benchmark Set of Crude Oils

1.1 Global Oil Climate Index Crude Oils

In March 2015, the Carnegie Endowment for International Peace published a report titled "Know Your Oil: Creating a Global Oil-Climate Index." The report measured the life cycle GHG emissions for 30 unique crude oils from around the world.

Phase 2 of the report was released in August 2016. The updated report increased the number of crude oils in the index from 30 to 75. The OCI website publishes data that describes the production and upgrading emissions assumptions for each of these 75 crude oils. This section explains the ARC Method for estimating the life cycle GHG emissions for the 75 crude oils using the input data provided by the OCI.

Crude Oil Production, Upgrading, and Transportation

The ARC Method uses the Stanford Oil Production Greenhouse Gas Emissions Estimator ("OPGEE") (version 1.1 Draft E) to generate the GHG emissions for crude oil production, upgrading, and oil transport. OPGEE is an Excel based model that allows a user to enter over 50 inputs related to the upstream production of a particular type of crude oil. The OPGEE model, along with detailed documentation, can be downloaded at Stanford University's website. [1]

In order to be consistent with the current best practices in GHG modelling, the ARC Method makes some minor adjustments to the default values contained within the OPGEE model. Most importantly, the global warming potential ("GWP") of methane is updated to reflect the latest values published by the Intergovernmental Panel on Climate Change ("IPCC"). [2]

1. To access the OPGEE model used in the ARC Method (version 1.1 Draft E) use the following link: https://eao.stanford.edu/research-areas/opgee
2. The 100 year GWP for methane was increased from 25 to 34 using data from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (AR5). IPCC Working Group I, "Climate Change 2013: The Physical Science Basis," *Intergovernmental Panel on Climate Change*, (2013), 714.

The ARC Method uses the same inputs as the OCI to model the production and upgrading emissions for each of the 75 crude oils. These inputs are available in the Author's Calculations Excel workbook and can be downloaded from the OCI website. [3] The unique inputs for each of the 75 crude oils were entered into OPGEE. In addition to entering the input data that describes the crude oil production, information on the distance and mode of transportation used for moving the crude oil from the production field to the refinery were also entered. Consistent with the inputs included in the OCI, the ARC Method assumes that the crude oils are refined in Houston, Texas.

Refining

The University of Calgary's Petroleum Refinery Life Cycle Inventory Model ("PRELIM") model (version 1.1) was used to estimate the refining emissions for each of the 75 crude oils. This model can be downloaded from the University's website. [4]

The main input into PRELIM is the crude oil assay. A crude oil assay describes the crude properties in detail by quantifying the amount and characteristics of the crude oil that is boiled off at each temperature range. PRELIM comes pre-loaded with over 110 crude oil assays, including all of the crude oils that are used in the OCI Phase 2 report.

Refineries differ greatly in their complexity, and typically the most complex refineries convert heavy crude oils into refined products, whereas simple refineries consume the lightest crude oils. To accommodate the varying range of refinery types, the PRELIM model includes three different refinery configurations. The most complex refinery is called a deep conversion refinery, and by default PRELIM assumes that the heaviest crude oils (API gravity of 22º and lower) are refined in these facilities. The model assumes that light, sweet crude oils (with API gravity over 32º) are processed in a simple refinery, known as a hydroskimming refinery. Finally, crude oils that do not fit into the light or heavy crude oil categories are assumed to be processed in a medium conversion refinery.

The ARC Method makes some minor adjustments to the PRELIM default values in order to be consistent with current best practices in GHG modelling. First, the GWP for methane is updated to reflect the latest values published by the IPCC. Secondly, the PRELIM model is adjusted to account for the production of liquefied petroleum gases ("LPG") from refinery off-gas. Both of these changes are consistent with the methodology used by the OCI.

After making these input changes and modelling each crude oil assay in PRELIM, the model returns an estimate of the emissions generated during the refining process for each of the 75 benchmark crude oils. The PRELIM model also calculates the volumes of the various refined products that are produced when each crude oil is processed in a refinery.

3. To download the Author's Calculations Excel workbook, use the following link: http://oci.carnegieendowment.org/assets/resources/oci-webtool-base-run.xlsx
4. The version of the PRELIM model used in the ARC Method (version 1.1) and the associated documentation can be found on the University of Calgary's website via the following link: www.ucalgary.ca/lcaost/prelim

Refined Product Transport

To estimate the emissions for transporting crude oil from the refinery to the retail station, the ARC Method uses a 2008 study from DOE/NETL. [5] The study estimated that the average GHG emissions for transporting refined products in the United States via pipeline are 2.39 kilograms of carbon dioxide equivalent per barrel ("kgCO_2e/barrel") of refined product.

This factor was applied to the PRELIM estimate of the total volume of refined products yielded from each crude oil. The ARC Method includes only liquid products and excludes emissions from the transportation of petroleum coke.

Combustion

To calculate the GHG emissions for the combustion of each benchmark crude oil, the ARC Method uses the PRELIM estimate of the volume of each liquid refined product [6] that is produced from a single barrel of crude oil. The volume of each fuel is multiplied by its specific carbon dioxide ("CO_2") emissions factor (see Table 1 in the Main Report – "CO_2 Emissions Factors for Combusting Refined Products") to arrive at the total emissions for burning all of the liquid refined products that are produced from a single barrel of crude oil.

As discussed in the Main Report, the ARC Method does not include the impacts from combusting petroleum coke. This is because due to the substitution of coal, the combustion of petroleum coke is not viewed as adding additional emissions to the atmosphere.

1.2 US Refined Average (2014)

This update to the ARC Method refreshes the US Refined Average baseline from 2005 to 2014. The updated baseline is based on data provided in a DOE/NETL study that was published in 2016; referred to as "the DOE/NETL (2016) study" [7] within this report.

The DOE/NETL (2016) study reports the GHG emissions for the US Refined Average (2014) using a refined products basis (i.e. carbon intensity per gallon of gasoline or diesel fuel); this differs from the ARC Method which uses a whole crude oil basis (see Section 2 in the Main Report "Basic Concepts in Measuring GHG Emissions for Crude Oil and the ARC Method," for more information on using different basis of comparisons).

The following section outlines the methodology used for estimating the US Refined Average (2014) baseline on a whole barrel of crude oil basis consistent with the ARC Method, using input data from the DOE/NETL (2016) study.

5. Kristin Gerdes and Timothy J. Skone, "Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels" *US Department of Energy National Energy Technology Laboratory*,(November 2008).
6. This includes blended gasoline, jet-A, ultra-low-sulfur diesel ("ULSD"), fuel oil, bunker fuel/liquid heavy ends, and LPG.
7. Gregory Cooney, Matthew Jamieson, Joe Marriott, Joule Bergerson, Adam Brandt, and Timothy J. Skone, "Updating the U.S. Life Cycle GHG Petroleum Baseline to 2014 with Projections to 2040 Using Open-Source Engineering-Based Models," *Environmental Science and Technology in Association with the US Department of Energy National Energy Technology Laboratory* 51, no. 2 (November 2016) 977-987.

Crude Oil Production and Upgrading

Similar to the ARC Method, the DOE/NETL (2016) study used OPGEE [8] to calculate the production and upgrading emissions for the major crude oil streams consumed by US refineries. [9] The DOE/NETL (2016) study also used similar boundaries and inputs, making their results comparable with the exception of a few minor differences.

One of the differences between the ARC Method and the DOE/NETL (2016) study was the use of different OPGEE input factors, specifically the flare destruction efficiency and the upstream emissions associated with supplying electricity and natural gas. DOE/NETL ran a sensitivity analysis on these factors and found that when compared with the OPGEE defaults, the new factors resulted in a decrease in emissions of 1 to 3 percent. [10] Therefore, to make the results comparable to the ARC Method (which uses default values for OPGEE), the production and upgrading emissions from the DOE/NETL (2016) study were increased by 2 percent.

After making the necessary adjustments to the production and upgrading emission values for each crude oil, the emissions were then weighted by the contribution of each oil to the total US refinery feedstock in 2014. [11,12] On average, ARC estimates that the production and upgrading emissions intensity for the US Refined Average (2014) is 59.0 kgCO_2e/barrel.

Crude Oil Transport

The DOE/NETL (2016) study published the OPGEE generated transportation emissions estimate for each crude oil included in the 2014 baseline. [13] After making adjustments to account for input differences (a 2 percent change as described above) and weighting each crude oil by its respective contribution to the total 2014 refinery feedstock, the crude oil transportation emissions intensity for the US Refined Average (2014) was estimated to be 3.6 kgCO_2e/barrel.

Refining

In accordance with the ARC Method, the PRELIM model was used to determine the refining emissions associated with each crude oil that was included in the 2014 baseline. The DOE/NETL (2016) study provides guidance for which pre-loaded PRELIM crude oil assay best describes each crude oil stream included in the 2014 baseline. [14]

8. The DOE/NETL (2016) study used a separate model to evaluate the oil sands, called the Greenhouse Gas Emissions of Current Oil Sands Technologies ("GHOST"). This model includes the same boundaries as the OPGEE model. Therefore, for the purposes of calculating the US Refined Average (2014), the results were treated as equivalent to the OPGEE results.
9. Cooney et al, "Updating the U.S. Life Cycle GHG Petroleum Baseline to 2014 with Projections to 2040 Using Open-Source Engineering-Based Models," Supplemental Information Table SI-26.
10. Ibid., Supplemental Information page SI-83, page SI-56.
11. Ibid., Supplemental Information Table SI-11, page SI-29.
12. The breakdown of US crude oil consumed in 2014 was provided by DOE/NETL on a mass basis, converted to a volume basis by ARC using the density of each crude oil.
13. Cooney et al, "Updating the U.S. Life Cycle GHG Petroleum Baseline to 2014 with Projections to 2040 Using Open-Source Engineering-Based Models," Supplemental Information Table SI-26, page SI-56.
14. Ibid., Supplemental Information Table SI-11, page SI-29.

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While the majority of the 2014 baseline crude oil assays are preloaded into PRELIM version 1.1, an analog method was used for missing crude oils (substituting the missing crude oil with another crude oil with similar density and sulfur content properties).

After adjusting the PRELIM model defaults to make them consistent with the ARC Method (described earlier in the Appendix in "Section 1.1 – Refining"), the PRELIM model was used to estimate the refining GHG emissions for each crude oil assay. The refining emissions for each crude oil were then weighted by the contribution to the total US refinery feedstock in 2014, yielding a refining emissions intensity value for the US Refined Average (2014) of 31.7 $kgCO_2e$/barrel.

Refined Product Transport and Combustion

In addition to refining emissions, the PRELIM model also calculates the mix of refined products produced from each crude oil. The ARC Method uses the volume of each refined product for calculating both the refined product transportation emissions and the combustion emissions. The results for each crude oil were weighted by their contribution to the total US refinery feedstock mix in 2014 on a volume basis. Based on this method, the refined product transportation and combustion emissions for the US Refined Average (2014) were estimated at 2.4 $kgCO_2e$/barrel and 413.8 $kgCO_2e$/barrel respectively.

Section 2: Evaluating the Carbon Risk of a Specific Crude Oil Investment

2.1 How to Estimate the Impact of a Carbon Levy on Investment Returns

Although life cycle analysis ("LCA") is a useful tool for comparing crude oils from the perspective of how many GHG emissions are emitted into the earth's atmosphere, other adjustments are needed to understand the range of carbon costs that could be borne by an investor in a specific oil production asset.

Assuming that crude oil facilities need to pay for the carbon they emit, the charge would apply to their direct GHG emissions only (i.e. the GHGs that are produced within the boundaries of the oil production site). As explained in Section 2 of the Main Report, the production and upgrading emissions estimate from the OPGEE model includes the direct GHG emissions, but it also considers a wider boundary, taking into account indirect effects of the production. This includes accounting for other emissions that are generated off-site (e.g. emissions for producing electricity at an off-site power plant), applying a credit for any by-products (natural gas, electricity, or natural gas liquids (NGLs)), and an estimate of the GHG impacts from land use change.

Since an oil production facility is not likely to be directly responsible for the emissions which occur upstream of the site, or for emissions due to land use, they do not need to be included in the estimate of the producer's carbon cost. Including the costs for these emissions would overstate the company's direct liability. Similarly, while applying a credit for by-products is appropriate when assessing emissions from a broad perspective, this method is less useful when examining the total carbon cost that a specific oil production facility may be burdened with. After all, under a carbon levy, an oil production facility will likely be responsible for all of the direct GHG emissions produced at the site, and will not get a credit for any by-products.

In addition to removing indirect emissions, an investor may still want to make further adjustments to the standard OPGEE output in order to determine the amount of direct emissions from methane losses versus CO_2 from combustion. Depending on the regulatory jurisdiction in which the oil production facility operates, each gas is likely to have a different type of policy applied. For example, CO_2 is likely to face a carbon levy and a methane reduction policy could require operators to change out equipment that releases methane to the atmosphere. Consequently, it is important to break the direct emissions into separate methane and CO_2 components. [15]

For some crude oils, the difference between the wide boundary emissions used in LCA and the narrower set of direct emissions for calculating a producer's carbon levy can be wide. Table A1 illustrates this point by showing, for each of the crude oils in the ARC benchmark set, the direct on-site emissions of CO_2 and methane (that an investor should use for calculating a carbon levy) versus the wide boundary life cycle GHG emissions for comparing the full scope of emissions released into the atmosphere.

For the crude oils that generate and export electricity or produce large volumes of associated natural gas, the producer's on-site direct GHG production emissions are much higher than when a wider boundary is considered. This is because the credit for by-products is not being applied. All things the same, if a carbon levy were introduced, then the facilities that produce by-products will tend to have higher absolute carbon costs. However, it is important to consider that while these by-products are often associated with higher carbon costs, they can also be valuable revenue streams for these facilities. For example, if a facility produces and sells excess electricity or natural gas then, along with paying a higher carbon cost, the asset will also be generating additional revenue, which helps to offset the carbon burden.

The producer's direct, on-site GHG emissions intensity is used to determine the potential impact of a carbon levy on investment returns. The first step is to make an estimate of a potential carbon cost for a specific asset. To do this the direct on-site emissions intensity for both CO_2 and methane must be multiplied by the expected levy on each of the gases; this will result in a per barrel carbon cost that can be considered as an additional cost for economic modelling.

As an example, assume the direct on-site emissions of CO_2 for an oil production site are 50 kgCO_2e/barrel and the direct on-site emissions of methane for the same site are 25 kgCO_2e/barrel. If an investor expects that a $30/tonne of CO_2e carbon levy will be brought in, and applied equally to CO_2 and methane, then this would equate to an extra cost of $2.25 for every barrel of crude oil produced ($1.50/barrel for CO_2 and $0.75/barrel for methane). These additional costs can be added to the investor's economic models to understand the implications of the carbon levy on investment returns. To understand the sensitivity of returns to differing levels of carbon price, the investor can repeat the calculation over a range of carbon prices.

15. See Section 3 of the Appendix for an example calculation for separating the emissions from carbon dioxide and methane using OPGEE outputs.

Table A1: Production and Upgrading Estimated GHG Emissions for Crude Oils - Comparing the Direct On-Site Emissions with the Wide Boundary LCA Emissions

Crude Oil	Direct On-Site Emissions of CO_2 ($kgCO_2e$/barrel)	Direct On-Site Emissions of Methane ($kgCO_2e$/barrel)	Total Direct On-Site Emissions ($kgCO_2e$/barrel)	Wide Boundary Emissions for Life Cycle Analysis ($kgCO_2e$/barrel)
Algeria Hassi R'Mel	111	167	278	99
Nigeria Obagi	119	133	252	154
Nigeria Bonny	104	131	235	128
US Texas Eagle Ford Condensate Zone	157	71	227	173
Indonesia Duri	196	16	212	143
US California Midway Sunset	178	19	197	179
Nigeria Escravos Beach	81	51	132	134
US Alaska North Slope	90	40	130	114
US Louisiana Lake Washington Field	106	22	128	135
Iraq Zubair	73	46	120	122
US California South Belridge	84	17	101	103
India Bombay High	52	39	91	94
China Bozhong	42	49	90	52
Nigeria Pennington	53	36	90	89
Venezuela Merey Blend	52	36	88	85
US Bakken Flare	58	25	84	80
Qatar Dukhan	49	28	77	75
Norway Oseberg	35	38	72	81
Norway Skarv	26	43	69	38
Russia Chayvo	33	35	68	52
Iran Marun	38	26	65	80
Libya Waha	30	34	64	51
Iraq Kirkuk	32	30	62	64
China Nanhai Light	29	30	59	60
Iraq Rumaila	32	27	59	66
Brazil Lula	31	28	59	56
US Wyoming WC	27	32	58	18
Qatar Bul Hanine	27	25	52	48
US California Wilmington	34	17	51	56
US East Texas Field	25	25	51	60
UK Forties - Average	32	19	51	54
Iraq West Qurna	25	25	50	69
US Gulf Mars	24	25	49	39
Indonesia Minas	25	25	49	44
Kuwait Ratawi	25	24	49	46
Nigeria Agbami	24	25	48	49
Ecuador Sacha	22	24	47	58
Iran Aboozar	20	25	45	42
Colombia Cusiana	21	24	45	44
US Texas Eagle Ford Volatile Oil Zone	20	24	44	31
Mexico Chuc	22	22	44	39
Denmark Dansk Blend	18	25	43	37
Angola Takula	20	23	43	38
US Texas Spraberry	16	27	43	41
United Arab Emirates Fateh	18	24	42	41
US Gulf Thunder Horse	21	21	41	38
US Wyoming Salt Creek	24	18	41	64
Australia Cossack	14	26	41	30
US Texas Eagle Ford Black Oil Zone	17	20	38	38
Azerbaijan Azeri Light	16	22	37	31
Saudi Arabia Zuluf	14	22	36	30
Mexico Cantarell	15	20	35	40
United Arab Emirates Murban	12	23	34	28
Russia Samotlor	15	19	33	39
Brazil Frade	12	19	31	30
Venezuela Tia Juana	15	15	30	54
Norway Ekofisk	11	19	30	24
Nigeria Bonga	9	20	29	25
Angola Girassol	10	19	29	26
US Bakken No Flare	10	18	28	19
Angola Kuito	10	17	28	28
Saudi Arabia Ghawar	9	19	27	26
Colombia Caño Limón	9	18	26	34
China Qinhuangdao	10	16	26	28
US Texas Yates	7	19	26	31
Kazakhstan Tengiz	8	17	26	25
Kuwait Burgan	6	18	24	22
Canada Hibernia	6	17	23	24
Russia Romashkinskoye	7	16	23	31
Saudi Arabia Safaniya	4	17	21	22

Source: ARC Energy Research Institute using input data from the Carnegie Endowment's Global Oil Climate Index

Note: oil sands and the US Refined Average (2014) are not included in this table

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2.2 Other Considerations for the Investor

Besides direct emissions, the investor could add other indirect carbon costs into their financial models. For instance, if a power plant has to pay a carbon levy, then the price of power for the oil producer may increase, and the investor may want to account for this potential cost in their calculations. Similarly, assuming that an oil refiner is burdened with a carbon levy, then more carbon intense crude oils could be subject to a price discount. These could be important considerations for an investor, however some caution is required. Market dynamics are complicated, and exactly how the burden of a carbon levy on a refinery or power generator would be shared between consumers, refiners and producers is uncertain.

Section 3: Putting it all Together: A Sample Calculation

The following applied example explains how to model the life cycle GHG emissions for a hypothetical oil field that produces light crude oil from the US Midwest. The sample calculation illustrates how to use the GHG emissions information to calculate a range of carbon costs. Following along with these steps and reproducing the results will illustrate how to apply the ARC Method to any crude oil investment.

Step 1: Gather Data about the Asset

The first step is gathering data to describe the characteristics of the oil field and its emissions. Previous research by Stanford University explains the four criteria that are the most important in estimating upstream GHG emissions: (1) steam-to-oil ratios (2) water-to-oil ratios (3) flaring rates and (4) crude oil density (measured by API gravity). [16] Other inputs that are also important to having precise measurements include: gas-to-oil ratios, oil production rates, and drilling depths (for extremely deep wells).

For this example calculation, these four essential inputs are included, along with some other basic data. OPGEE defaults are used for most other inputs, with the exception of a change to the GWPs. Refer to Table A2 for all of the inputs used to describe the example oil field.

Step 2: Model the GHG Emissions for Crude Oil Production and Transportation

Next, you must enter the data that describes the oil field into the OPGEE Excel model (version 1.1 Draft E). The input values and the location within the model for inputting data are listed in Table A2.

After inputting all of the data, OPGEE will automatically generate an estimate of the GHG emissions for producing and transporting the crude oil. The emissions are summarized in the "User Inputs & Results" tab of the

16. For more information on this topic, you can refer to Kourosh Vafi and Adam R. Brandt's "Uncertainty of Oil Field GHG Emissions Resulting from Information Gaps: A Monte Carlo Approach," *Environmental Science and Technology* 48, no. 17 (2014): 10511-10518. Additionally you may also refer to Adam R. Brandt, Yuchi Sun, and Kourosh Vafi's, "Uncertainty in Regional-Average Petroleum GHG Intensities: Countering Information Gaps with Targeted Data Gathering," *Environmental Science and Technology* 49, no. 1 (2015): 679-686.

Table A2: Input Data for Hypothetical Oil Field in the US Midwest

Input	Sheet	Cell	Value	Units
Field Name	User Inputs & Results	J67	Example Field	
Field Depth	User Inputs & Results	J69	11,000	Ft
Oil Production Volume	User Inputs & Results	J70	5,800	bbl/d
Number of Producing Wells	User Inputs & Results	J71	32	#
Number of Water Injecting Wells	User Inputs & Results	J72	17	#
Crude Oil API	User Inputs & Results	J78	41	deg. API
Gas-to-Oil Ratio	User Inputs & Results	J90	1,020	scf/bbl
Water-to-Oil Ratio	User Inputs & Results	J91	0.6	bbl water/bbl oil
Ratio of Flaring to Oil Production	User Inputs & Results	J107	182	scf/bbl
Water Injection Ratio	User Inputs & Results	J92	1.6	bbl water/bbl oil
Fraction of Oil Transported by Each Mode (Ocean Tanker, Barge, Rail)	User Inputs & Results	J125, J126, J128	0	#
Fraction of Oil Transported by Each Mode (Pipeline)	User Inputs & Results	J127	1	#
Transport Distance (Pipeline)	User Inputs & Results	J132	1,971	Miles (distance is based on Midwest to Houston)
Global Warming Potentials (CO)	Input Data	C72	0	GWP
Global Warming Potentials (CH4)	Input Data	C73	34	GWP
Global Warming Potentials (VOCs)	Input Data	C74	0	GWP
Flare Destruction Efficiency	Flaring	M48	95	%
Crude Oil Sulfur*	-	-	0.3	%

Source: ARC Energy Research Institute
*Note: Crude oil sulfur is not used in OPGEE, but is needed in Step 4 of the example calculation.

OPGEE model in "Table 1.1: Summary GHG Emissions."[17] Table A3 in this report shows the OPGEE output for the sample crude oil. The first two columns of Table A3 are directly from the OPGEE model, while the other columns and footnotes illustrate the conversion from OPGEE's original units into the units of kgCO2e/barrel using the lower heating value of the crude oil found in Cell M15 of the "Fuel Specs" tab.

OPGEE reports the total emissions (including both production and crude oil transportation) in the "Net Lifecycle Emissions" row. To derive the emissions for the crude oil production step only, you must subtract the "Transport" emissions (4.90 kgCO2e/barrel) from the total "Net Lifecycle Emissions" (54.46 kgCO2e/barrel) to arrive at crude oil production emissions of 49.56 kgCO2e/barrel.

17. Note: Depending on the version of Excel you are using, you may need to enable macros for OPGEE to function properly.

Table A3: OPGEE Output of Production and Transportation Emissions and ARC Calculations

OPGEE Output		ARC Calculations*	
	GHG emissions (gCO_2eq/MJ)	Convert gCO_2e/MJ to $kgCO_2e/barrel$ using Lower Heating Value (MJ/barrel)	GHG Emissions ($kgCO_2e/barrel$)
	0.00		
Exploration	0.00		
Drilling	1.47		
Production	0.40		
Processing	0.86		
Upgrading	0.00		
Maintenance	0.00		
Waste	0.00		
VFF	6.45		
Diluent	0.00		
Misc.	0.50		
Transport	0.89	5530.15	4.90
Offsite emissions	-0.72	5530.15	-3.99
Net lifecycle emissions	9.85	5530.15	54.46
Production and Upgrading Emissions - ARC Method			**49.56**

Source: OPGEE, ARC Energy Research Institute

*The OPGEE table displays the results in gCO2e/MJ. To convert the units to kgCO2e/barrel, the crude oil's lower heating value is required. The lower heating value is found in Cell M15 of the OPGEE Model's "Fuel Specs" tab. This value will depend on the API gravity of the crude oil modelled. To convert the results from the units of gCO2e/MJ to kgCO2e/barrel, multiply the OPGEE GHG emissions in the second column by the lower heating value in the third column, and then divide the total by 1000 g/kg, this results in the value found in the fourth column in units of kgCO2e/barrel.

Step 3: Model the GHG Emissions for Crude Oil Refining

The PRELIM model (v1.1) is used for generating two outputs: (1) The GHG emissions associated with refining the crude oil, and (2) the volume of each refined product (gasoline, diesel, fuel oil, etc.) that can be produced from one barrel of crude oil (the latter output is used in Steps 4 and 5).

The PRELIM model comes pre-loaded with data that characterizes the properties of more than 110 unique crude oils. If your crude oil is not found in the pre-loaded list, then you can choose a crude oil analog by selecting a PRELIM crude oil that has similar properties (API gravity and sulfur). While using an analog crude oil is not as accurate as having the actual crude oil assay, it is the most practical method. [18]

18. The PRELIM model does provide the option for entering a new crude oil assay. However, it can be difficult to find assays with enough detail, and even then PRELIM requires a specific format.

To help in the selection of analog crude oils, Table A4 lists the density and sulfur content of the crude oils that are pre-loaded in PRELIM version 1.1. The crude oil for this hypothetical example has an API gravity of 41^{o} and 0.3 wt percent sulfur. After looking through Table A4, PRELIM's "West texas intermediate_Stratiev" crude oil assay is the closest to the example crude oil. Once deciding to use this crude oil assay, return to the "Main Input & Output" tab of the PRELIM model and choose "West texas intermediate_Stratiev" from the "Pick a crude assay" drop box.

Before the results can be read, a few inputs must be changed in order to be consistent with the ARC Method. First, the production of liquid petroleum gas must be turned on. This toggle slider is found in cell C134 of the "Main Input & Output" tab. Next, the GWP values must be updated to reflect the IPCC values used in the ARC Method. This is done by selecting the fifth option "2013 IPCC AR5 (100 years, with CCF)" in the drop down menu located in cell C110 of the "Main Input & Output" tab.

After selecting the crude oil and changing the necessary inputs, PRELIM automatically calculates the GHG emissions for refining the crude oil in cell W34 of the "Main Input & Output" tab. For the example crude oil, the model calculates refining emissions of 17.86 $kgCO_2e$/barrel.

Step 4: Model the GHG Emissions for the Transportation of Refined Products

To estimate the GHG emissions for transporting the refined products to the consumer via pipeline, the volume of all the liquid refined products is needed. PRELIM displays the volume of each product that is produced by a refinery in a single day in the "Results Single Assay" tab. In order to determine the amount of products per barrel, the volumes must be divided by the total crude oil volume fed to the refinery (99,745 barrels/d of crude oil is used for this example, found in cell E12 of the "Assay Inventory" tab).

Table A5 shows the output for a coking refinery from PRELIM as well as the ARC Method for calculating the emissions for transporting refined products. In this example, the total amount of liquid refined products is similar to the amount of crude oil feedstock, with a total of 0.999 barrels per day of refined products per barrel of crude oil consumed by the refinery. Using the refined product transport emissions factor described in Section 1.1 of this Appendix (2.39 $kgCO_2e$/barrel of refined product), the total refined product transportation emissions are 2.39 $kgCO_2e$/barrel of crude oil.

Step 5: Model the GHG Emissions for the Combustion of Refined Products

To estimate the GHG emissions from the combustion of the refined products from a barrel of crude oil, the volumes of each refined product calculated in Step 4 are needed again. The volume of each product is now multiplied by the emissions factor for that particular product (provided in Table 1 in the Main Report – "CO_2 Emissions Factors for Combusting Refined Products"). Table A6 shows how to calculate the combustion emissions for the products of one barrel of crude oil, excluding the petroleum coke. For this example crude oil, the total GHG emissions for combustion are 412.04 $kgCO_2e$/barrel of crude oil.

Table A4: PRELIM Version 1.1 Crude Oil Inventory and Properties

Crude Oil	API Gravity	Sulfur (Wt Percent)
Algerian Condensate_BP	68.4	0.0
Snohvit Condensate_Statoil	61.3	0.0
Margham Light_Ceric Emir	50.3	0.0
Nigeria Agbami_Statoil	48.0	0.1
Nigeria Agbami_Chevron	47.9	0.1
Cossack_Chevron	47.3	0.1
Tengiz_Chevron	46.4	0.7
Indonesia Tangguh_BP	44.1	0.1
Eagle Ford Ultralight_Platts	43.1	0.1
Dukhan_Qatar_COA	41.8	1.6
West texas intermediate_Stratiev	40.8	0.3
Forties_Chevron	40.3	0.8
UAE Murban_BP	40.1	0.9
Norway Oseberg_Statoil	39.7	0.2
Nanhai Light_Chevron	39.5	0.0
Kirkuk_O&G	39.3	2.0
UAE DAS Blend_BP	39.3	1.2
Forties_Statoil	38.7	0.8
Forties Blend_BP	38.6	0.7
Olmeca_COA	38.6	0.8
Brent_Exxon	38.5	0.6
Ekofisk_BP	38.4	0.2
Ekofisk_Statoil	38.4	0.2
Ekofisk_Chevron	38.4	0.3
Bakken_Various Sources	38.4	0.1
Brent_Chevron	38.2	0.4
India Bombay_COA	37.9	0.1
Brent_BP	37.4	0.3
Wyoming Sweet_COA	37.2	0.3
Light Sour Blend_Crude Monitor	37.1	1.1
East Texas Sweet_COA	37.0	0.3
Russia Sokol_Exxon	36.4	0.4
Cusiana_COA	36.4	1.0
Siberian Light_COA	36.2	0.5
Azeri light_Exxon	36.1	0.2
Louisiana light sweet_Stratiev	36.1	0.3
Azeri Light_Chevron	36.1	0.1
Nigera Quaib_Exxon	36.0	0.1
Norway North Sea Skarv_BP	36.0	0.4
Libya Es Sider_COA	35.7	0.2
Nigeria Pennington_Chevron	35.4	0.1
Canada Hibernia_Statoil	35.0	0.5
High Sour Edmonton_Crude Monitor	34.9	1.3
Nigera Erha_Exxon	34.8	0.2
Azeri Light_Statoil	34.8	0.2
Canada Hibernia_Exxon	34.6	0.6
West texas sour_Stratiev	34.1	1.3
Sumatran Light (Minas)_Chevron	33.9	0.1
Syncrude Synthetic_Crude Monitor	33.6	0.2
Canada Hibernia_Chevron	33.5	0.6
Nigeria Escravos_Chevron	33.5	0.2
Suncor Synthetic A_Crude Monitor	33.5	0.2
North Sea Dansk Blend_Statoil	33.5	0.3
Thunderhorse_BP	33.5	0.7
Arab Light_Stratiev	33.4	1.6
Isthmus_Stratiev	33.3	1.3
Thunderhorse_Exxon	32.9	0.8

Crude Oil	API Gravity	Sulfur (Wt Percent)
Bonny Light_Chevron	32.7	0.2
Syncrude Sweet Premium_Crude Monitor	32.7	0.2
Marine Qatar_O&G	32.6	2.1
Husky Synthetic Blend_Crude Monitor	32.6	0.1
Russian Export Blend_Stratiev	31.8	1.3
Angola Cabinda_Stratiev	31.7	0.3
Alaskan North Slope_Exxon	31.4	0.8
Kuwait Export_Stratiev	31.4	2.3
Fateh_COA	31.1	1.9
Iranian Heavy_COA	31.0	1.5
Nigera Bonga_Exxon	30.6	0.2
Iraq Basra_BP	30.2	2.7
Angola Girassol_Exxon	29.9	0.3
Angola Girassol_Statoil	29.8	0.4
Midale_Crude Monitor	29.6	2.3
Basrah Medium_COA	29.6	2.7
Brazil Lula_BG Group	29.3	0.3
Colombia Cano Limon_Stratiev	29.3	0.6
Ecuador Oriente_Stratiev	29.2	0.9
Mars USA-Gulf of Mexico_BP	28.8	1.6
Arab Medium_Stratiev	28.5	2.4
Arab Heavy_Stratiev	27.4	2.3
Iran Ardeshir_COA	26.9	2.5
Hamaca Venezuela_Knovel	26.0	1.6
Basrah Heavy_O&G	24.7	8.1
Kuwait Ratawi_Chevron	24.2	5.0
Venezuela Leona_COA	24.1	1.3
Congo Emeraude_Stratiev	23.6	0.8
Burgan (Wafra)_O&G	23.3	3.4
Midway-Sunset_Knovel	22.6	1.2
Christina Lake_Crude Monitor	22.2	3.5
MAYA_Stratiev	22.2	3.3
Angola Kuito_Chevron	22.1	0.9
Bow River North_Crude Monitor	21.1	2.7
Wabasca Heavy_Crude Monitor	20.9	4.0
Lloyd Blend_Crude Monitor	20.9	3.7
Cold Lake_Crude Monitor	20.7	3.9
Western Canadian Blend_Crude Monitor	20.6	3.3
Seal Heavy_Crude Monitor	20.6	5.1
Lloyd Kerrobert_Crude Monitor	20.6	3.3
Western Canadian Select_Crude Monitor	20.5	3.4
Indonesia Duri_Chevron	20.3	0.2
Brazil Polvo_BP	20.3	1.0
Albian Residual Blend_Crude Monitor	20.0	3.2
Smiley-Coleville_Crude Monitor	19.9	3.0
Suncor Synthetic H_Crude Monitor	19.9	3.1
Brazil Frade_Chevron	19.8	0.8
Synbit Blend_Crude Monitor	19.8	3.0
Albian Heavy Synthetic_Crude Monitor	19.5	2.2
Wilmington CA_Knovel	19.4	1.6
Kuwait Eocene_Chevron	18.3	5.3
China Bozhong_Chevron	16.9	0.3
Qin Huang Dao_Chevron	16.5	0.3
Belridge_Knovel	15.0	0.2
Merey_O&G	14.7	2.1
Venezuela Tia Juana_Stratiev	12.1	2.5

Source: PRELIM

Table A5: Calculation of the Estimated GHG Emissions for Transporting Refined Products for Hypothetical Crude Oil Example

PRELIM Output			ARC Calculations		
Product Slate	%	Bbl Product Per Day	Convert to Barrel of Crude Oil Basis	GHG Emissions Factor for Transporting Fuel ($kgCO_2e$/barrel of Refined Product)	Transportation GHG Emissions from all Liquid Fuels ($kgCO_2e$/barrel of Crude Oil)
Blended Gasoline	31.51%	30,783.35	0.309	-	-
Jet-A/AVTUR	23.83%	23,275.36	0.233	-	-
ULSD	8.12%	7,929.82	0.080	-	-
Fuel Oil	8.67%	8,472.48	0.085	-	-
Coke	0.00%	0.00	0.000	-	-
Liquid Heavy Ends	27.87%	27,224.37	0.273	-	-
Surplus Refinery Fuel Gas (RFG)	0.00%	0.00	0.000	-	-
Liquified Petroleum Gas (LPG)*	-	2,007.54	0.020	-	-
Total			**0.999**	**2.39**	**2.39**

Source: PRELIM, US Department of Energy National Energy Technology Laboratory, ARC Energy Research Institute

* Barrels of LPGs are not shown in the PRELIM output by default. Instead the user must convert the mass of LPGs produced, shown in Cell D50 of the "Results Single Assay" tab as 162,149 kg/d, to volume using the density of 80.77 kg/barrel.

Table A6: Calculation of the Estimated GHG Emissions for Combusting Refined Products for Hypothetical Crude Oil Example

PRELIM Output			ARC Calculations		
Product Slate	%	Bbl Product Per Day	Convert to Barrel of Crude Oil Basis	GHG Emissions Factor for Combusting Fuel ($kgCO_2e$/barrel of Refined Product)	Combustion GHG Emissions from all Liquid Fuels ($kgCO_2e$/barrel of Crude Oil)
Blended Gasoline	31.51%	30,783.35	0.309	370.3	114.28
Jet-A/AVTUR	23.83%	23,275.36	0.233	411.1	95.93
ULSD	8.12%	7,929.82	0.080	429.8	34.17
Fuel Oil	8.67%	8,472.48	0.085	462.1	39.25
Coke	0.00%	0.00	0.000	-	-
Liquid Heavy Ends	27.87%	27,224.37	0.273	452.8	123.59
Surplus Refinery Fuel Gas (RFG)	0.00%	0.00	0.000	-	-
Liquified Petroleum Gas (LPG)*	-	2,007.54	0.020	239.7	4.82
Total			**0.999**	**-**	**412.04**

Source: PRELIM, EPA, ARC Energy Research Institute

* Barrels of LPGs are not shown in the PRELIM output by default. Instead the user must convert the mass of LPGs produced, shown in Cell D50 of the "Results Single Assay" tab as 162,149 kg/d, to volume using the density of 80.77 kg/barrel.

Step 6: Compare the Life Cycle Emissions of the Crude Oil to the Other Sample Oils

With all the LCA stages now calculated, each stage is added together to arrive at the total life cycle emissions for our hypothetical crude oil (see Table A7).

The life cycle GHG emissions values for the hypothetical US Midwest crude oil can now be compared to the benchmark crude oils that are detailed in Table 3 of the Main Report. At 486.75 kgCO2e/barrel on a well-to-combustion basis, this particular crude oil is 4.4% below the US Refined Average (2014). On a crude oil production basis, the crude is 16% below the US Refined Average (2014). This ranking is helpful for getting a notional sense of how the GHG footprint of this crude oil compares to others, and how the overall competitiveness of that crude oil may be impacted in a carbon constrained world. However, in order to get a more precise estimate of the direct impact of a carbon levy on the oil asset, the direct GHG emissions are required. This is discussed in Step 7.

Step 7: Evaluate the Impact of a Potential Carbon Tax on your Investment Returns

More stringent GHG emissions policies would increase the cost for emitting GHGs. If the policy put in place is a carbon levy, then a producer will be responsible for paying a fee related to their direct emissions of CO_2 (from combustion) and/or methane (that has escaped into the atmosphere). To estimate the direct financial burden from a carbon levy on a crude oil asset, an investor must calculate the quantity of CO_2 and/or methane released directly from their oil production site, excluding the indirect emissions as well as emissions from land use change that are not assumed to fall under a carbon levy.

OPGEE does not separate out CO_2 and methane in the main results it displays, but due to the transparent nature of the model, the breakdown can be calculated from the model outputs. For combustion emissions, the OPGEE model separates emissions into two main sources: combustion from flaring, and all other combustion from oil field operations. For methane, there are three main sources: vented methane, fugitive methane, and methane released due to incomplete combustion during flaring. The following formulas in Table A8, along with the variables described in Table A9 demonstrate how to calculate the total direct emissions from combustion and methane emissions from the OPGEE outputs.

In this example, the emissions from combustion are 21.83 kgCO_2e/barrel and the emissions from released methane are 24.78 kgCO_2e/barrel. Using these values, an investor can make an estimate of the extra cost per barrel of a carbon levy on both direct combustion and methane emissions.

To calculate the carbon cost, an investor must first make an assumption of the taxes on a per tonne of CO_2e basis for each gas and then multiply those taxes by the appropriate emissions intensity value. Tables A10 and A11 show the estimated carbon cost on a per barrel of oil basis for the hypothetical example under a range of carbon levy assumptions. A different range of carbon costs is used for combustion and methane emissions as some policy makers are planning to treat each gas separately. Once estimated, the extra carbon costs can then be added to an economic model of the crude oil asset in order to understand how these costs could impact future investment returns.

It is important to note that these costs are illustrative only, in reality carbon policy may have a different level of costs and could require actions beyond paying a levy.

This hypothetical US Midwest oil field example was meant to aid those who wish to apply the ARC Method to their own investment portfolio. After following this step-by-step example, and completing each stage, investors should be in a better position to apply the ARC Method for estimating the cost of carbon policy on any crude oil asset.

Table A7: Total Well-to-Combustion Estimated GHG Emissions for Hypothetical Crude Oil Example

Stage of Life Cycle	Emissions (kgCO_2e/barrel)
Production and Upgrading	49.56
Crude Oil Transportation	4.90
Refining	17.86
Refined Product Transportation	2.39
Refined Product Combustion	412.04
Total: Well-to-Combustion	486.75

Source: ARC Energy Research Institute

Table A8: Formulas for Calculating Combustion and Methane Emissions from Oil Production

$$(1)\ Combustion\ Emissions = \frac{1}{1000}\left(\frac{(C+F_{All}-N*GWP_{CH4})}{P} + M*LHV\right)$$

$$(2)\ Methane\ Emissions = \frac{(V+G+N*GWP_{CH4})}{1000*P}$$

Table A9: OPGEE Variables for Calculating Combustion and Methane Emissions from Oil Production

Variable		OPGEE Location	Value in Example	Units
C	Combustion from Operations	'GHG Emissions'H51	47,328,227	gCO_2e/d
F_{all}	Flaring (CO_2 & CH_4)	'GHG Emissions'K51	93,456,836	gCO_2e/d
V	Venting	'GHG Emissions'J51	99,679,425	gCO_2e/d
G	Fugitives	'GHG Emissions'L51	13,827,553	gCO_2e/d
LHV	Lower Heating Value	'Fuel Specs'M15	5,530	MJ/bbl
P	Production per day	'User Inputs & Results'J70	5,800	bbl/d
N	Non-Combusted Methane From Flaring	'Flaring'M61	889,000	g/d
GWP_{CH4}	Global Warming Potential of Methane	'Input Data'C73	34	GWP
M	Misc. Emissions	'User Inputs & Results'C19	0.5	gCO_2e/MJ

Source: ARC Energy Research Institute

Table A10: Combustion Emissions, Additional Cost Per Barrel Under Different Carbon Levy Scenarios

Combustion Levy Scenario ($/tonne of CO_2e)	Direct On-Site Emissions of CO_2 from Combustion ($kgCO_2e$/barrel)	Carbon Cost on Each Barrel Due to Combustion Levy ($/barrel)
30	21.83	0.65
50	21.83	1.09
60	21.83	1.31

Source: ARC Energy Research Institute

Table A11: Methane Loss Emissions, Additional Cost Per Barrel Under Different Carbon Levy Scenarios

Methane Levy Scenario ($/tonne of CO_2e)	Direct On-Site Emissions of Methane ($kgCO_2e$/barrel)	Carbon Cost on Each Barrel Due to Methane Levy ($/barrel)
10	24.78	0.25
20	24.78	0.50
30	24.78	0.74

Source: ARC Energy Research Institute

Glossary of Key Terms

API Gravity

API gravity is a measure of density for petroleum products. The measuring scale is calibrated in terms of API degrees. The lower the API gravity measure, the heavier the crude oil. In the PRELIM model and for the ARC Method, a crude oil is considered to be heavy when it has an API gravity measure of 22° and lower. A crude oil is considered to be light when it has an API gravity measure over 32°, and when the API gravity measure is between 22° and 32°, it is considered to be a medium crude oil.

Bakken Formation

The Bakken Formation is an oil producing play in the Williston Basin. Recently, the use of horizontal drilling and fracturing technology has allowed for rapid oil production growth in the play, mainly in North Dakota.

Crude Oil Assay

A detailed profile of a crude oil, an assay reports the volume and quality of the crude oil that is boiled-off in each temperature range. This profile commonly includes properties such as the density and sulfur content to define the characteristics of a specific crude oil.

Deep Conversion Refinery

The most complex type of refinery, it includes a coker process unit that converts the heaviest part of the crude oil barrel into light transportation fuels. The PRELIM model assumes that the heaviest crude oils in their model will be refined in a deep conversion refinery.

Density

A measure of the compactness of a substance, density is expressed in units of mass per unit of volume.

Eagle Ford Shale

The Eagle Ford Shale is an oil and gas producing play in South Texas. The rock is notably brittle, making it a prime target for oil and gas extraction through hydraulic fracturing. As a result of horizontal drilling and hydraulic fracturing, oil production has been growing rapidly from the play in recent years.

Flaring Rates

Many oil wells produce natural gas alongside the crude oil. Often the natural gas is captured and sold as a by-product of the crude oil production. Sometimes, however, due to infrastructure constraints or for economic reasons, the natural gas is not captured. Instead, the gas is combusted in a flare at the well site.

GHG Intensity

The ratio of greenhouse gases produced for each unit of product. For example, in the case of crude oil production, GHG intensity is measured by the mass of CO_2 equivalent gas created for each barrel of crude oil extracted.

Global Warming Potential ("GWP")

An estimate of the relative effect of a particular gas molecule at trapping heat within the earth's atmosphere on a mass basis. CO_2 is normalized to have a GWP of 1, so that all other gas molecules are measured relative to CO_2 for their ability to trap heat within the atmosphere.

Hydroskimming Refinery

The simplest type of refinery, it separates the crude oil into petroleum fuels and improves the properties. The refinery does not have the ability to convert heavier parts of the crude oil into lighter liquids. The PRELIM model assumes that the lightest crude oils in their model are refined in hydroskimming refineries.

Internal Rate of Return ("IRR")

A metric used to evaluate the profitability of an investment. It is the interest rate at which the net present value of all cash flows (both positive and negative) from a project or investment is equal to zero.

Liquified Petroleum Gas ("LPG")

A mix of natural gas liquids primarily made up of propane and butane.

Medium Conversion Refinery

Sometimes called a cracking refinery, it includes a Fluid Catalytic Cracking unit that converts the middle part of the crude oil barrel into light transportation fuels. The PRELIM model assumes that medium crude oils are processed in a medium conversion refinery.

Natural Gas Liquids ("NGLs")

Raw natural gas from the wellhead is mostly comprised of methane but also contains various other heavier hydrocarbons such as ethane, propane, butane and pentanes plus. These heavier hydrocarbons are referred to as NGLs.

Petroleum Coke

When heavy crude oil is converted into lighter fuels in a deep conversation refinery using a coker, the process creates a solid by-product that is similar to coal, called petroleum coke.

Steam-to-Oil Ratio

For some heavy oil plays, steam is injected into the reservoir to produce the oil. The measure of the volume of steam used to produce one barrel of oil is called the steam-to-oil ratio.

Upstream

In the oil and gas industry, the term upstream refers to operations that deal with exploration and extraction of crude oil and natural gas. Upstream does not include any processing of the raw crude oil or natural gas, these activities are considered part of the midstream and downstream operations.

US Tight Oil

Refers to the light crude oil found in tight reservoirs. As the oil is trapped in low permeability rocks, horizontal drilling and hydraulic fracturing are used to enable the hydrocarbons to flow to the wellbore.

Water-to-Oil Ratio

Many oil wells produce water alongside the crude oil. The ratio of produced water to produced oil is the water-to-oil ratio.