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# Assessment of Direct and Indirect GHG Emissions Associated with Petroleum Fuels

For New Fuels Alliance

Life Cycle Associates, LLC

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## Summary

The production and use of transportation fuels include a wide range of activities that contribute to greenhouse gas (GHG) emissions over their life cycle. Traditional fuel life cycle analyses compare a range of alternative fuels to petroleum fuels on a well-to-wheel (WTW) basis including feedstock production, transport to refining, refining into multiple products, delivery to end markets and vehicle emissions. Recent analyses of the life cycle impacts of biofuels have expanded the boundaries to include indirect effects of ethanol production such as land use change (LUC) impacts on soil $CO_2$ and $N_2O$ emissions, and the impact of land use change on crop production and cattle stock (Searchinger 2008).

This study reviews the range of activities associated with the production of petroleum fuels in order to assess their life cycle impact on GHG emissions. This includes both direct petroleum emissions, and to the degree feasible, some indirect effects. Included are effects such as road construction and co-product residual oil use, which are not typically included in studies of petroleum GHG emissions. A system boundary definition is provided for determining which GHG sources are included in the life cycle of petroleum; including a working definition of what constitutes a direct or indirect effect. Comparing the life cycle for different fuel options, requires a clear and consistent definition of the system boundary both in terms of geography as well as the scope of effects that are compared.

Calculations of the average emissions in the GREET model are examined and compared with those associated with marginal and unconventional petroleum resources. This study also examines how emissions from average production resources differ from more recent and costly resources on the margin. Emission sources associated with exploration, land use, co-product residual oil, and indirect effects such as the effects of the military activity and deforestation associated with road construction are also examined.

## Direct and Indirect Effects

A working definition of direct effects includes those related to the energy and material inputs associated with the operation of petroleum infrastructure. GHG emissions associated with petroleum fuels are of interest in the context of reducing GHG emissions through efficiency and other fuel options. Therefore, the development of petroleum projects, oil exportation, and construction of facilities is of interest when examining the production of billions of gallons of transportation fuels. The direct effects identified in Table S-1 include the process energy inputs and vehicle operation emissions typically included in fuel life cycle studies. Emissions associated with facility construction, exploration, and land-clearing are also the direct effect of the production of the new petroleum fuel capacity.

Indirect effects, on the other hand, are inherently more difficult to quantify. A working definition of indirect effects includes those related to either price-induced or behavioural changes in the marketplace. In the case of biofuels, indirect land use change (iLUC) is a price-induced indirect effect. The categories considered here include effects that are not part of the operation of petroleum infrastructure such as deforestation enabled by road building for petroleum projects or military activities that are attributed to the protection of oil supplies. The use of refinery co-products also has an indirect effect on energy markets.

Table S-1 examines to what extent direct and indirect emissions have been included in petroleum fuel life cycle analyses. Traditional fuel cycle analyses focus on average oil production, refining, transport and vehicle use. Some studies also examine the requirements for heavy oil and oil sands production. The energy inputs and emissions associated with oil exploration are typically not examined. In circumstances such as Californian and Canadian oil resources, the location of oil resources has been established for decades. However, new off shore oil resources require ongoing exploration activities and more energy-intensive extraction technologies. The energy inputs and emissions associated with the production, refining and transport of petroleum often reflect the average petroleum infrastructure. However, considerable variation in energy requirements is apparent in crude types; thus at a minimum, the range in GHG emissions associated with petroleum infrastructure is understated.

The question of refinery emissions is a more complex topic because of the range of inputs, transportation of fuel products, and heavy co-products. Processing requirements vary with crude oil sulphur content, gravity (also related to carbon content), and other aspects of its assay. Considerably more analysis is needed to properly partition emissions within the oil refinery and understand the effects of different crude types. Since oil refining is such a complex process, it is not surprising that a consistent approach for treating oil refining is not applied among different life cycle studies.

The impacts of facility construction are often considered comparable among fuel options. However, oil exploration and land clearing associated with oil sands are unique to the petroleum industry. In order to provide a consistent representation of the inputs used to produce petroleum fuels, the emissions associated with these activities should be included in life cycle assessments in a clear and comparable manner.

Military activities associated with the protection of oil supply are often attributed to the use of gasoline. The emissions associated with the protection of oil supply are categorized as indirect effects because there is no straightforward approach to relating a direct process throughput with military activity. The effects of protection of oil supply can include military activities in the Middle East, the effects of the Iraq wars, as well and the post war effects on both reconstruction and U.S. troops. However, it is difficult to agree on an approach for identifying, and quantifying, the direct vs. indirect effects of military activity.

Additional indirect effects correspond to the use of co-products associated with oil refining. For example, GHG emissions from residual oil and petroleum coke combustion exceed those from all of the alternative fuels used in the U.S. today. These emissions are treated with various allocation schemes in life cycle analyses. The effects of substitute products and the carbon intensity of petroleum co-products need to be examined further as the modelling approach requires further scrutiny.

**Table S-1.** Categorization of direct vs. indirect effects of petroleum production.

| Petroleum Supply Option | Direct Effects | | | | | | | | | | Indirect Effects | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Oil Exploration | Oil Production | Methane losses, flaring | Oil Refining | Oil and Product Transport | Land Use Conversion | Tailing lakes, $CH_4$ | Vehicle fuel | Exhaust minor species | Material inputs | Refinery Co-products | Macro Economic Effects | Protection of oil supply | Iraq Reconstruction | Indirect land Use |
| Venezuelan Heavy | ⦿ | ⦿ | ⦿ | ⦿ | ◎ | ⦿ | – | ● | ● | ○ | ⦿ | ⦿ | ⦿ | ⦿ | ⦿ |
| Canadian Oil Sands | ● | ◎ | ⦿ | ◎ | ◎ | ⦿ | ⦿ | ● | ● | ⦿ | ⦿ | ⦿ | – | ⦿ | – |
| Iraqi | ⦿ | ⦿ | ⦿ | ◎ | ◎ | – | – | ● | ● | ○ | ⦿ | ⦿ | ⦿ | – | – |
| Nigerian | ⦿ | ⦿ | ⦿ | ◎ | ◎ | – | – | ● | ● | ○ | ⦿ | ⦿ | – | – | – |
| California TEOR | ● | ⦿ | ⦿ | ◎ | ◎ | ⦿ | – | ● | ● | ○ | ⦿ | ⦿ | – | ⦿ | – |
| U.S. Off Shore | ⦿ | ⦿ | ⦿ | ◎ | ◎ | – | – | ● | ● | ⦿ | ⦿ | ⦿ | – | – | – |
| Conventional | ⦿ | ● | ● | ◎ | ◎ | ⦿ | – | ● | ● | ○ | ⦿ | ⦿ | – | – | – |

●Included in traditional[a] fuel life cycle analysis

○Excluded from traditional fuel life cycle analysis because relative difference among fuels is small

⦿ Not included in traditional full fuel life cycle analyses

◎Include in traditional fuel life cycle analyses and requires additional study

– Not applicable

[a] Delucchi's work on fuel life cycle analysis includes many of the effects in this table or recommends work in these areas.

[b] Market effects of petroleum would also include induced effects on land use.

Broader economic or price-induced petroleum effects are difficult to systematically assign a boundary given the prevalence of oil-induced economic drivers in the world economy. However, to the extent that economic effects are considered a part of the life cycle analysis of alternative fuels, as is the case with iLUC for biofuels, their effect vis-à-vis petroleum is also of interest. The effect of changes in petroleum supply and price will effect global goods, their movement, and the use of resources and their related GHG emissions. Petroleum dependence and oil price fluctuations influence a wide range of worldwide markets, ranging from agricultural commodity prices to the cost of living and doing business. Economic effects clearly require further study as market effects have proven to cause more of an effect than government regulatory measures.

### *Results*

The GHG impact of petroleum estimated herein ranges from 90 to 120 g $CO_2$e/MJ (grams of $CO_2$ equivalent emissions per megajoule (MJ) of gasoline fuel consumed), depending on the source of the petroleum and to what extent indirect emission impacts are included. The high end reflects unconventional resources and heavy oil, which can contribute to over 10% of current supplies. These emission estimates do not include all of the effects discussed in this report as some effects – most notably the broader economic, price-induced effects of the marginal gallon of petroleum – require further analysis. The range of GHG emissions for average petroleum based transportation fuels used in the U.S. is often reported as having an uncertainty band of +/- 1 to 2 g $CO_2$e/MJ. When indirect impacts, marginal resources, and uncertainties discussed in this report are taken into account, the range in emissions is considerably greater.

It is critical to consider these results in their proper context. They represent an initial estimate of various examples of the marginal gallon of petroleum, inclusive of many traditionally omitted direct effects and a limited, incomplete number of indirect effects. Attempting to quantify the marginal gallon of petroleum is important because, in many cases a life cycle comparison of fuels is based on expanding the use of alternative fuels and thereby displacing a marginal gallon of gasoline. Environmental benefits for fuel regulations are also based on life cycle analyses. The appropriate calculation of the emissions impact would correspond to the marginal gallon of displaced petroleum or avoided capacity expansion.

The differences in GHG emissions among petroleum sources depend on the energy requirements for extracting and processing the fuels, variations in fugitive emissions, as well as indirect effects. Indirect effects range from military activities to protect Middle Eastern oil supplies or the destruction of native forest due to the construction of roads and associated activities. Tertiary oil extraction technologies such as thermal enhanced oil recovery or steam recovery of oil sands result in increased GHG emissions compared to the conventional extraction and processing of Canadian oil sands, CA heavy thermally enhanced oil recovery and Venezuelan heavy oil.

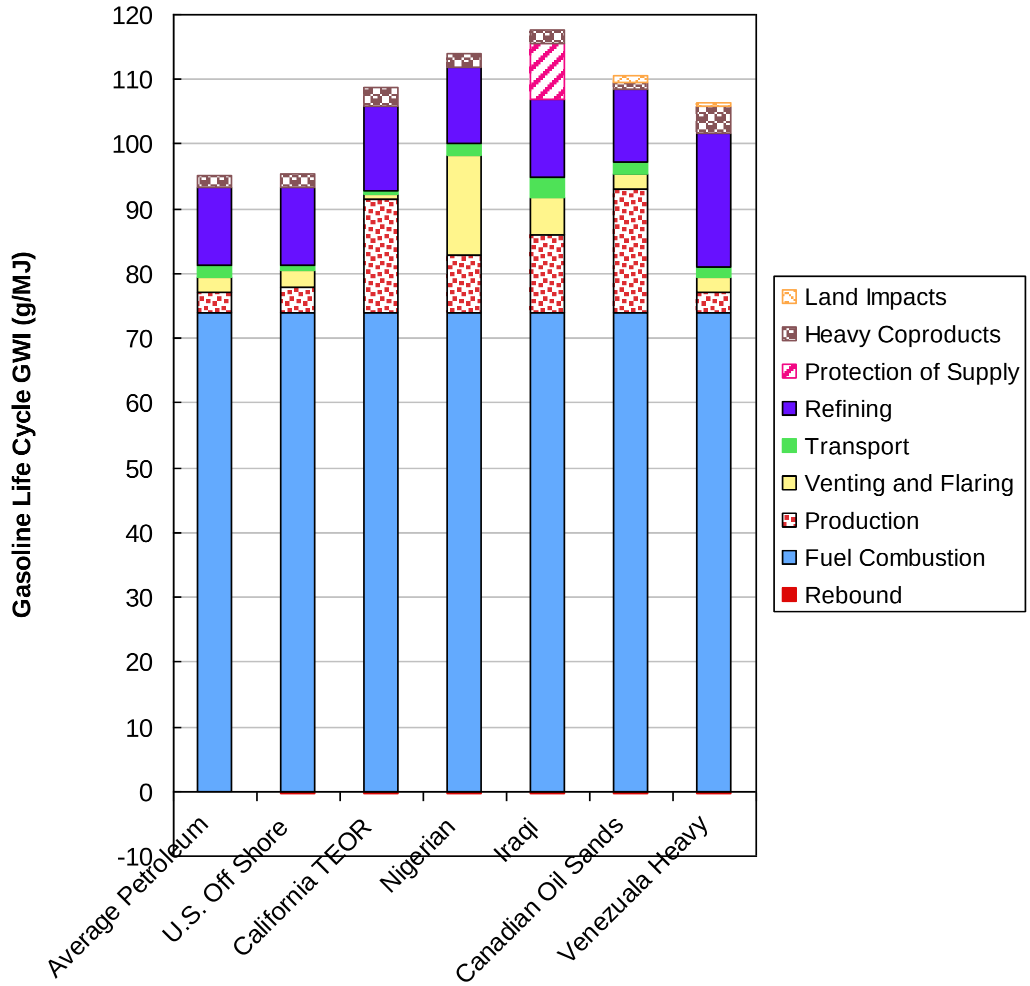


**Figure S-1.** Summary of GHG Emissions for Different Crude Oil Production Scenarios.

The key differences between the petroleum supply options in Figure S-1 correspond to emission sources that are typically not included in fuel life cycle studies. Emissions that are found on the margin are considerably higher than expected. The source of oil is also highly dependent on the extraction methodology. Canadian oil sands, for example, require more processing and when assessing land use, Canadian oil sands naturally require more land. However, some direct effects, such as refinery outputs, are thus far poorly understood and require more scrutiny in order to evaluate them. Other direct emission impacts need to be better understood including the emissions associated with the conversion of forests for the surface mining of oil sands and mine by-waste products that are stored in lakes.

Indirect effects are largely omitted from the majority of other petroleum studies. However, even when co-products are included, an emissions increase of several percent for all transport fuels can be calculated. A broader set of economic effects can also be calculated and a consistent measurement of these effects is required. Several equilibrium modeling approaches could address some of the economic aspects of petroleum fuels.

## *Conclusions*

As depicted in Figure S-1, production of petroleum fuels involves numerous energy and economic impacts that affect the global GHG emissions associated with fuel consumption. Many of the impacts of oil production are examined in well published fuel life cycle studies, which primarily use average energy inputs and emissions. However, the variety of emission sources associated with petroleum production is often omitted from life cycle studies.

The GHG emissions associated with the production and use of petroleum fuels are still uncertain, particularly for fuels on the margin. The supply chain requires additional study as many of the methods used to estimate GHG emissions are still poorly developed. However, co-products and heavy refining do account for high outputs as can be seen in the case of Venezuela Heavy Crude. This is also apparent as a result of increased venting and flaring in Nigeria, the protection of oil in Iraq and the production of Canadian oil sands.

Calculations in this study indicate that the fate of residual oil and petroleum coke is important, and a potentially significant source of GHG emissions, but require further economic modeling. The magnitude of carbon emissions associated with these products indicates that a detailed analysis of their fate and the effect on other fuel markets should be examined.

The definition of a direct vs. indirect effect may remain vague. The debate as to whether the Iraq war, for example, is an effect that occurs as a direct or indirect result of petroleum dependence will continue. It could be argued that an indirect effect of the war, and therefore petroleum use, might include health effects and long term Middle East presence by the western world. Nonetheless, the magnitude of the emissions directly associated with military activity is readily calculated. More analysis may improve the readers' perspective but opinions are likely to remain diverse.

Higher oil prices and dwindling light crude stocks induce development of more costly, energy intensive petroleum resources that have higher than average life cycle GHG emissions. These marginal supplies are associated with:

- Tertiary oil recovery
- Production of heavy oils
- Production of oil sands derived fuel
- Imports of finished product from remote locations in relatively small vessels
- Production from small capacity stripper wells

Once projects are completed and operational the oil produced becomes part of the world oil supply. Hence, the average GHG emissions are expected to increase and new marginal supplies are likely to have even higher greenhouse emissions. Nonetheless, high cost, energy intensive marginal resources must be factored into current and future projections of the impact of petroleum based transportation fuels to the extent that marginal considerations are taken into account for alternative fuels.

**Terms and Abbreviations**

| | |
|---|---|
| ANL | Argonne National Laboratory |
| API | American Petroleum Institute |
| bbl | Barrel |
| bcm | Billion cubic meters |
| bhp-h | brake horse power-hour |
| Btu | British thermal unit |
| CEC | California Energy Commission |
| CGE | Computational general equilibrium |
| $CH_4$ | Methane |
| $CO_2$ | Carbon dioxide |
| CPI | Consumer Price Index |
| DC | Developing Country |
| DDGS | Dried distillers grains with soluble |
| DoD | Department of Defense |
| DOE | Department of Energy |
| DWT | Deadweight |
| ECA | Emissions Control Areas |
| EIA | Energy Information Administration |
| EIO-LCA | Environmental Input Output Life Cycle Assessment |
| EPA | Environmental Protection Agency |
| FAPRI | Food and Agricultural Policy Research Institute |
| FASOM | Forest and Agricultural Sector Optimization Model |
| FSU | Former Soviet Union |
| ft | Feet |
| gal | Gallon |
| GEMIS | Global Emission Model for Integrated Systems |
| GHG | Greenhouse gas |
| GM | General Motors Corporation |
| GREET | Greenhouse gas, Regulated Emissions and Energy Use in Transportation (Argonne National Laboratory's well-to-wheels model) |
| GTAP | Global Trade Analysis Project |
| GTL | Gas to liquid |
| GWI | Global warming intensity |
| ha | Hectare |
| H/C | Hydrogen/Carbon ratio |
| HFO | Heavy fuel oil |
| IEA | International Energy Agency |
| IFO | Intermediate fuel oil |
| IMO | International Maritime Organization |
| IPCC | Intergovernmental Panel on Climate Change |
| J | Joule |
| JEC | Joint Economic Committee |
| kJ | kilo joule |

| | |
|---|---|
| km | kilometer |
| kWh | kilowatt hour |
| LCA | Life cycle assessment |
| LCFS | Low Carbon Fuel Standard |
| LCI | Life cycle inventory |
| LPG | Liquefied petroleum gas |
| LUC | Land use change |
| iLUC | Indirect Land use change |
| Mbbl | Million barrels |
| Mboe | Million barrels of oil equivalent |
| Mg | Mega gram, 1 metric ton |
| MIT | Massachusetts Institute of Technology |
| MJ | Mega joule |
| mm Btu | Abbreviation for million Btu for English units |
| NASA | National Aeronautics and Space Administration |
| NG | natural gas |
| $N_2O$ | Nitrous oxide |
| NOAA | U.S. National Oceanic and Atmospheric Agency |
| OECD | Organization for Economic Co-operation and Development |
| OPEC | Organization of the Petroleum Exporting Countries |
| PADD | Petroleum Administration for Defense Districts |
| PJ | Peta Joule, $10^{15}$ Joules |
| PwC | Price-Waterhouse-Coopers |
| RBOB | Reformulated blend stock for oxygen blending |
| RCF | RCF Consulting of Chicago |
| RFG | Reformulated gasoline |
| SAGD | Steam Assisted Gravity Drainage |
| $SO_2$ | Sulfur Dioxide |
| UK | United Kingdom |
| UN | United Nations |
| USDOC | United Stated Department of Commerce |
| USAID | United States Agency for International Development |
| U.S. | United States |
| TEOR | Thermally enhanced oil recovery |
| Tg | Terra gram, $10^6$ metric tonnes |
| tonne | metric ton, 1000 kg |
| TTW | Tank to wheels |
| WBCSD | World Business Council for Sustainable Development |
| WTT | Well to tank |

## Table of Contents

## Lists of Figures and Tables

### Tables

## Figures

# 1. Introduction

Traditional life cycle analyses of fuels provide a limited assessment of the emissions associated with petroleum derived fuels and their associated uncertainties. Broad studies such as those completed by General Motors Corporation (GM) in collaboration with Argonne National Laboratory, the European Union, and others (Wang 1999, Brinkman 2005, Edwards 2007) compare a wide range of fuels and technologies to a gasoline baseline. Similar boundary conditions are applied to the numerous variants of hypothetical or low volume commercial fuels such as hydrogen or dimethyl ether and petroleum fuels are treated as a well known quantity. Other studies have looked at petroleum fuels in more detail (Bergerson 2006, Brandt 2005) by investigating the range in emissions associated with petroleum fuels. However, the GHG impacts that are examined are limited primarily to the set of traditional direct impacts – emissions associated with process fuel consumption and methane losses.

Recent analyses of the life cycle impacts of biofuels have expanded the boundaries to include indirect effects of ethanol production such as land use change (LUC) impacts on soil $CO_2$ and $N_2O$ emissions, and the impact of land use change on crop production and cattle stock (Searchinger 2008).

All LCAs set boundary conditions on what will be included. Typical boundary conditions for transportation fuels includes petroleum extraction, transportation of the crude, refining, transportation of the finished product, and its use. What is normally not included entails:

- The energy associated with the building of plants, pipelines, etc.
- Land use impacts including deforestation induced by forest roads and land cleared for tar sands development
- Indirect economic effects associated with primary fuel production and co-products

In addition, it is recognized that activities associated with the protection of petroleum supplies in unstable parts of the world also result in military activities such as:

- Military activities to protect oil supply
- Military activity and effects of the first and second (Iraq) wars
- Post-war reconstruction activities

In recent years some of the alternative fuels life cycle analyses have expanded their boundaries to include land use effects and other inputs further from the production and use stages. Because of the need to compare the impacts of various fuel/vehicle options on a uniform basis, it is necessary to determine the impact of similar boundary changes to the petroleum life cycle of transportation fuels.

There is debate over the definition and analytical inclusion of indirect LUC effects on petroleum and biofuel production. For instance, the Searchinger article states:

> "*The amount of land used to produce a gallon of gasoline is extremely small — according to some energy experts we have quickly consulted, it is less than 1 percent of the amount of land used to produce a gallon-equivalent of ethanol. Much of the world's oil is either produced in deserts or offshore or on land that still remains in productive agricultural use. Because the effect of oil production on emissions from land use change is small, it is reasonable to omit it".*

Consistency with the intent and significant detail of traditional fuel cycle analyses postulates inclusion rather than exclusion of 'insignificant values'. Moreover, the differences in carbon intensity between various compliance fuels relative to each other and petroleum in a carbon-based performance standard is very small, which implies that relatively small effects could be significant within a carbon-based fuel regulation. Still there is justifiable difficulty in measuring indirect effects- as they often are not at the capacity level and therefore are often not physical effects.

The GREET model is inclusive of many of the direct effects of petroleum production, and calculates these with intense scrutiny and precision. However, some variables such as Nigerian natural gas flaring of heavy oil production and upgrading in Venezuela are not so easily measured. Even with GREET covering over 100 fuel production pathways and over 80 vehicle-fuel systems, the emissions from such fuel production scenarios reflect significant departures from the default GREET inputs.

The debate over life cycle GHG emissions calculations, in terms of what variables to include and what, if any, to exclude, has prompted this study. The aim is to examine the impact of expanding the boundary conditions for the production and use of petroleum based transportation fuels to include a number of direct and indirect effects that are consistent with the requirements to produce petroleum fuels. A grouping of direct and indirect effects is shown in Table 1. The categories, developed here, provide a framework for categorizing life cycle emissions.

The direct effects are related to the primary energy inputs and emissions associated with fuel production. These include activities that are required to produce an additional unit of fuel, which include crude oil production, refining, distribution and vehicle end use considered in traditional fuel cycle analyses. To the extent that this question is interesting in the debate surrounding fuel options and GHG emissions, direct emissions would include activities associated with significant usage and therefore would include emissions associated with finding new oil, clearing land, and building production and refining facilities.

Indirect effects encompass all effects related to fuel production other than the energy and emission impacts directly associated with feedstock extraction, refining, transport, and vehicle operation. Many of the indirect effects of fuel production are induced by market forces of supply and demand. Others may be the consequence of government policy.

**Table 1.** Groupings of Direct and Indirect Emission Effects.

| |
|---|
| <u>Direct Effects</u><br>• Oil Exploration<br>• Oil Production<br>• Methane losses, flaring<br>• Oil Refining<br>• Oil and Product Transport<br>• Land Use Conversion<br>• Tailing lakes, $CH_4$<br>• Vehicle fuel Exhaust minor species<br>• Material inputs |
| <u>Indirect Effects</u><br>• Refinery Co-products<br>• Macro Economic Effects<br>• Protection of oil supply<br>• Iraq Reconstruction<br>• Indirect land Use |

Indirect effects can be addressed within the traditional LCA boundary, but fluctuate due to changing economic conditions and are thereby induced. For example:

- Shift to heavier and unconventional crude oil supplies
- Price pressures on gasoline with decreased/increased biofuels supply
- Price pressures on refinery inputs such as natural gas
- Price pressures on agricultural commodities from petroleum prices

Of course there are the indirect effects that are outside the traditional LCA boundary, such as road building and military activity. Included are:

- Emissions from U.S. government military activities in defense of Middle East oil
- Increased material use (i.e. cement) for war zone reconstruction
- Oil field fires due to military activities
- Road building to increase access and therefore increase deforestation

All other effects are grouped as indirect effects, which includes both economic impacts and other consequences of producing petroleum fuels. Table 4 summarizes the direct and indirect effects in a structured manner. The categories reflect the authors' grouping of the direct effects that occur with additional throughput or production capacity and are inputs to petroleum infrastructure. The indirect effects occur because of petroleum production activities but they are not part of the petroleum supply chain. The framework of petroleum effects provides the basis for the organization of this report.

The purpose of this study is to examine the direct and indirect effects of petroleum fuels. It develops a definition of direct and indirect effects, and examines what is included in existing fuel life cycle models. The study also examines and quantifies emissions that are not widely included in fuel life cycle analyses and develops recommendations to provide an improved understanding of the range of emissions associated with the production and use of petroleum fuels. This study should not be interpreted to include the full spectrum of indirect effects from petroleum, as many of the broader economic, price-induced effects are not quantified here because additional analysis must be conducted to deduce reasonable numerical estimations for these effects.

A list of the project tasks and the work breakdown structure is given in Table 2. The project team reviewed the range of emission impacts associated with petroleum production to assess how petroleum fuels are incorporated in life cycle analysis and what impacts are not included. First the analysis scope of the GREET model was examined. Then the range of fuel production impacts were identified and screened to assess their potential magnitude. Preliminary estimates of the life cycle GHG emissions were calculated. Many of the effects of petroleum processing include only specific resource options and production pathways, while others are broadly applicable. The GHG impacts associated with different petroleum resources and production pathways are then compared with the impacts related to each pathway.

The impact due to changes in the use of marginal petroleum sources are examined by investigating a range of petroleum production options. The analysis is framed in the context of a reduction in petroleum usage that would be consistent with the incremental increase in biofuels and other alternative fuels in the U.S. This might include an additional 10 billion gal/year of corn based ethanol and another 20 billion gallons per year of cellulose, sugar cane, and other biofuel based ethanol. In contrast, many fuel life cycle studies focus on average emissions. For example, the GREET model's default values for petroleum fuels and ethanol reflect average emissions for the U.S. This study examines how emissions from the average production resources differ from newer and more costly resources on the margin.

**Table 2.** Project Tasks.

| Task | Description |
|---|---|
| 1 | **System Boundary Definition** |
| | • Define scope of traditional life cycle analysis<br>• Define average versus marginal analysis requirements<br>• Define direct and indirect impacts of petroleum |
| 2 | **Life Cycle Inventory Data** |
| | • Identify scoping calculations for key data gaps<br>• Calculate inputs to determine GHG emissions<br>• Determine process input assumptions |
| 3 | **Petroleum Production Effects** |
| | • Calculate direct effects per MJ of fuel<br>• Estimate indirect effects and calculate per MJ fuel<br>• Review market mitigated effects (price elasticity)<br>• Describe complex attribution, driven by assumptions |
| 4 | **Impact on Life Cycle Assessment** |
| | • Develop petroleum scenarios<br>• Estimate range of direct and indirect impacts |

## 2. Scope of Petroleum Life Cycle Emissions

A traditional petroleum production LCA measures the life cycle GHG impacts associated with the production of petroleum fuels. The calculation methods are applied on a process specific or regional basis. These calculations present GHG emissions on an intensity basis, thus the functional unit of analysis is a MJ of gasoline. The life cycle analysis of petroleum is examined from exploration through vehicle end use, or a well to wheel basis. Both direct and indirect impacts and co-products are examined. It identifies market mitigated drivers; however, a much more extensive economic modeling effort is needed to formally assess these impacts.

A life cycle analysis of petroleum fuels should follow a set of procedures to determine how the study is conducted[1]. ISO 14044 (ISO 2006) provides requirement that have been applied to fuel life cycle studies. Specifically:

> *ISO 14040 specifies requirements and provides guidelines for life cycle assessment (LCA) including: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases, and conditions for use of value choices and optional elements.*

The first step in a life cycle analysis is to determine the scope of the study and asks the following three questions:

- Why is the study being conducted?
- What effects are important?
- What emissions are included?

The life cycle of petroleum fuels is generally of interest because the introduction of significant quantities of alternative fuels are being considered world wide. Government policies, technology improvements, and other factors are often targeted to displace 10 to over 30% of petroleum usage, including growth in capacity ((DOE 2008, CEC 2003, RTFO (UK)). Therefore, the scope of the petroleum life cycle analysis of interest should be consistent with such large reductions in output.

### 2.1. System Boundaries

In general, the system boundary for fuel production includes material inputs, resource extraction, production, vehicle use, and end of life activities. Many fuel life cycle studies perform a process based analysis that accounts for the direct energy inputs and emissions associated with fuel production. The process based analysis allows the system boundary to be drawn tightly and avoids endless smaller secondary material inputs and economic effects. A

[1] This scope of this study is not a complete life cycle assessment and is determining what should be included in the life cycle assessment and what is missing.

process based analysis also allows for the calculation of differences among petroleum options such as low sulfur fuels.

The traditional system boundary for petroleum fuels is shown in Figure 1. The analysis accounts for the direct energy inputs for oil production, transport, refining, and vehicle use. Process energy inputs are calculated for petroleum, natural gas, and other energy inputs. The results can be presented for RFG blends by combining the life cycle results for the reformulated blendstock for oxygenate blending (RBOB) with ethanol. This analysis is typically accomplished by calculating the RBOB life cycle through the refinery and then delivery of 100% RBOB. The energy content weighted average life cycle results for RBOB and ethanol represent the life cycle of the oxygenated blend. Since the life cycle of RBOB includes no significant contribution from ethanol, showing the results for RBOB alone represents the petroleum derived component of gasoline.

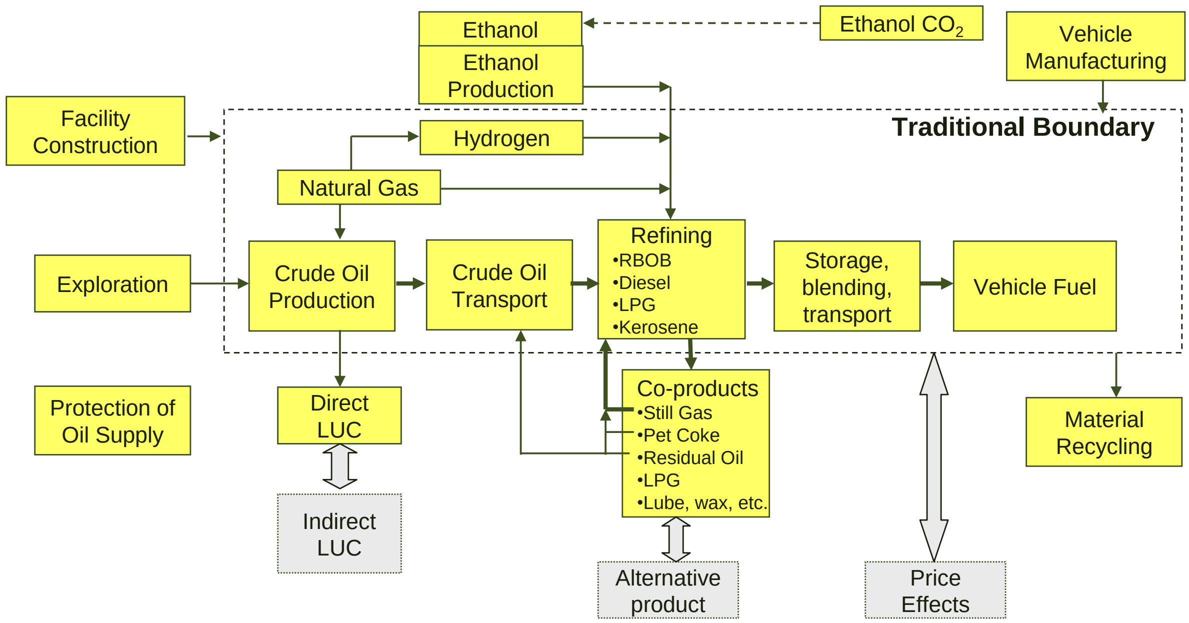


**Figure 1.** System boundary for petroleum fuel production and vehicle use.

The impacts of petroleum fuels are presented on a gasoline basis. Refineries produce a mix of fuel products including diesel, jet fuel, kerosene, LPG, and lubricants as well as heavy co-products. The energy assigned to refining diesel fuel is comparable or slightly less than that of gasoline. Therefore, the gasoline representation reflects the effects described in this report.

Fuel life cycle analyses exclude a variety of effects. Facility construction energy and material inputs are a small part of the fuel cycle and are often omitted from LCAs for petroleum studies. As discussed previously, these effects are debatable as to inclusion (or not) into LCAs for not just petroleum analyses but also of LCAs on biofuels.

GREET calculates the emissions associated with farm tractors to demonstrate that the result is small (for corn based ethanol production). The MIT (Weiss) life cycle study of fuels includes material inputs as it examines a range of vehicle technologies taking into account the energy inputs for materials in batteries and aluminum intensive vehicles. For most alterative fuel options, the energy intensity of material inputs is comparable to those for petroleum fuels.

Petroleum refining results in a range of products complicating the attribution of refinery inputs and emissions to fuel products. Fuel cycle analyses typically assign energy inputs and emissions to refinery co-products and exclude the GHG emissions associated with the co-products from the total assigned to gasoline and diesel fuels. Some of the co-products of the fuel cycle are used to produce transportation fuels. For example refinery marine bunker fuel is used to transport crude oil. Some refinery products are refinery inputs. Residual oil, petroleum coke, LPG, jet fuel, and other products are treated as co-products with various allocation approaches. The various approaches are discussed later in this report (Section 3.6.1).

Life cycle studies provide only a limited characterization of the range of fuel cycle impacts. The use of petroleum fuels also has indirect impacts such as the use of energy associated with U.S. policies aimed at the protection of Middle Eastern oil supplies, impacts on land use, and price effects. These effects are often cited as important economic impacts but the GHG emissions associated with these is generally not examined. Note that these are outside of the traditional boundary shown in Figure 2. (Notable exceptions in Delucchi 2008, Delucchi and Murch 2008).

Because the GREET model is extensively used in the life cycle analysis of fuels and fuel policies in the U.S., the model itself effectively defines a system boundary. The extent of the calculations in GREET's system boundary assumptions are discussed in the following section.

## 2.2. GREET Model Scope

The GREET model includes a variety of petroleum and non petroleum pathways[2]. The configurations of the model and default values calculate average energy inputs and emissions. The default values represent aggregate results for petroleum and alternative fuels that represent the average for U.S production. The model also calculates emissions for new fuels, where the process assumptions reflect new facilities while crude oil, existing biofuels, and electric power resources reflect the average from existing facilities.

For petroleum pathways, GREET calculates the energy inputs and emissions in 5 primary components:

- Crude oil production
- Crude oil transport
- Oil refining
- Product transport (Gasoline, Diesel, LPG)
- Vehicle end use

[2] The discussion here refers to GREET 1.8, released in September 2008. The discussion generally applies to its predecessors dating back to 1999.

The first four components are calculated and presented on a WTT basis with GHG emissions in g/mmBtu. The vehicle end use phase is calculated on a WTW basis and presented in g/mi. This phase includes the carbon in the vehicle fuel as $CO_2$. VOC and CO are counted as $CO_2$ with no double counting of carbon. Methane from vehicle exhaust and $N_2O$ are treated as GHG emissions according to their global warming potential.

Many of the inputs allow for the calculation of emissions to a great degree of precision. For example fuel spills from vehicle fuelling (0.5 g out of 8 gallons of vehicle fuelling) correspond to 0.002 g/MJ of GHG emissions. This model feature is useful because it allows for an understanding of the relative contribution of different fuel species. While hydrocarbons from spills are relatively minor GHG sources, they represent a significant portion of total hydrocarbon emissions. The great precision applied to many aspects of the calculations implies that the GHG emissions are well established, even when some inputs exhibit considerable variability.

The underlying assumption in GREET is that new oil, electricity, and other energy resources will consist of a comparable resource mix as existing resources. Default GREET inputs and the overall model structure do not reflect marginal fuel production or the impact of new fuels and savings in fuel usage.

Table 3 summarizes the treatment of the steps in the fuel and vehicle cycle in the GREET model. GREET inputs are intended to represent the U.S. average values for both production and refining. The first category in the GREET model is petroleum production, which includes the emissions associated with crude oil production equipment as well as fugitive losses. Energy inputs for heavy oil refining or unconventional oil production are not explicitly included in the model as it aims to provide an average aggregate result. These data are based on aggregate U.S. statistics (USDOC), which range from 0.047 to 0.025 J/J crude oil representing all of the fuel inputs used for oil production including natural gas, crude oil, electric power, and other energy sources. These values correspond to a crude oil extraction efficiency of 96 to 97.5% on the GREET input basis for the years 1997 and 2002 respectively. The GREET default input value is 98% with a resource mix comparable to the 2002 data. A comparable input parameter for the CONCAWE study is 0.025 J/J (Edwards).

Emissions related to venting and flaring associated gas are included in the GREET model with estimates representing data for the U.S. These values are adjusted to represent higher levels for overseas associated gas. The next step in the petroleum based fuel production process is crude oil transport, which includes both pipeline and limited barge transport and tanker ship transport for imported oil. Interestingly, the default GREET assumption for version 1.8b and prior versions indicates a 1,000,000 DWT tanker ship; which corresponds to 4 times the capacity of the typical marine tanker vessel in use today. This implies that the transportation GHG emissions for petroleum may be significantly higher than predicted by GREET.

The approach for attributing refinery energy inputs and emissions is another key assumption embedded in the GREET model. The GREET model assigns energy inputs and emissions associated with crude oil refining to each of the refinery products. U.S. refinery statistics provide the basis for estimating total refinery energy inputs. ANL's estimate of the energy inputs for each refinery unit and the product outputs are based on refinery models (Wang

2004) and provide the basis for allocating energy inputs among refinery products. The procedure treats transportation fuels and heavy oil co-products in the same manner, assigning refinery energy and emissions to their production. These estimates are adjusted with more recent EIA data for refinery energy (Wang 2008). The refinery energy inputs for each product (gasoline blend stock, LPG, diesel) are represented as a "refinery efficiency" value for each product. This approach eliminates the complexity associated with tracking the fate of different co-products. Several other approaches to the treatment of refinery energy have been implemented in life cycle studies. These are discussed in Section 4.1.

The "refinery efficiency" input assigns energy inputs to gasoline, diesel and LPG production. The analysis does not directly take into account the fate of co-product coke and residual oil that is produced when additional crude oil is processed. This is the case even though the coke and residual oil are substantial outputs within the refining cycle. The model calculates feedstock energy losses in refining processes separately from feedstock converted to fuel with the notion that 1 million Btu of feedstock is required to produce 1 million Btu of fuel product. The implications are discussed in Section 3.6.

Several emission sources are excluded because they represent a small fraction of the fuel cycle. For example, chemical inputs that are consumed in small quantities or replaced during maintenance such as catalysts are not included in GREET. Material inputs for facilities are not included in the model as a matter of system boundary definition. ANL also calculates some material energy inputs (for farming equipment) and demonstrates that the impacts are small. Thus, the GREET analysis does not further calculate material inputs for the comparison of fuel options because these emissions are a relatively small fraction of the fuel cycle.

GREET 2.7 calculates vehicle material inputs and emissions (Burnham). These emissions would be almost identical among comparable liquid fueled vehicles. The range in crude oil production emissions are represented by a stochastic simulation of uncertainty. The model or documentation does not explicitly identify data that are associated with the uncertainty analysis parameters available in the stochastic simulation.

**Table 3.** Treatment of Fuel Cycle Categories for Petroleum Pathways in the GREET Model.

| **Category** | **Treatment in GREET** | **Comments** |
|---|---|---|
| Facility Materials | Not included | Small component of fuel cycle. |
| Exploration and Drilling | Not included | Assumed to be small. |
| Venting and Flaring | Included in crude oil production | Data for U.S. adjusted to reflect composite value of domestic production and imports. |
| Crude Oil Production | 98% crude oil extraction efficiency assumption applied to feedstock | Based on aggregate U.S. statistics (USADC). Crude oil extraction emissions are inconsistently applied to downstream energy inputs. |
| Refining | Allocation to refinery products | Refinery energy inputs based on aggregate EIA statistics for the U.S. Allocation to gasoline is based on experience with refinery models with estimate of process specific allocation to gasoline. Inputs do not demonstrate a material balance. |
| Refining Co-products | Allocation to co-products | Upstream fuel cycle emissions are implicitly allocated to co-products as inputs to GREET. The selection of "refining efficiency" reflects the distribution of refinery emissions to transportation fuels. |
| Chemical Inputs | Not included | Small component of fuel cycle. |
| Fuel Cycle Calculations | Sum of WTT impacts | 1 mm Btu of Crude oil "feed" × loss factor +<br>Refinery energy + distribution |
| Vehicle emissions | TTW calculation | Fuel carbon + vehicle $N_2O$ and $CH_4$ shown on a per mile basis. |
| Vehicle manufacturing | GREET 2.7 analysis | Calculates material inputs and recycling for vehicles. Results are very similar for conventional vehicles and identical for blends. |
| Indirect, Market-Mediated Impacts | None | GREET applies a market factor to reduce the amount of credit applied to corn DDGS from corn ethanol by 15%. No other market impacts are included in GREET. |

The indirect impacts of petroleum production including economic effects, land use, and government policies associated with oil production are not included in the GREET model.

## 2.3. Marginal Impacts

The energy inputs and emissions associated with the production of the nth gallon of fuel represent the impact of a change in transportation fuel usage. Changes in petroleum usage could be due to a displacement by alternative fuels, improvements in fuel economy or a change in consumption behavior. In principle, the highest cost producers provide the marginal gallon of fuel. Cost factors include transport distance, tariffs, fuel specifications, as well as well as inputs to crude oil extraction and refining. The marginal argument is often applied to criteria pollutant emissions from new fuel production facilities in California (CEC 2005, Unnasch 2001) where a growth in alternative transportation fuels was projected to displace gasoline imports. However, the effect on global gasoline production is less clear.

One of the reasons that it is important to consider the marginal impact of petroleum – or the impacts of the marginal gallon of petroleum – is to ensure that fuels are compared equitably with regard to their carbon intensity scores. For example, as discussed, recent analyses of the life cycle impacts of biofuels have expanded the LCA system boundaries to include the price-induced, indirect effects of ethanol production, such as LUC, based on future ethanol demand measured in the world economy (i.e. the nth gallon of ethanol).

If the comparison is to petroleum, it is important to consider the impact of a marginal gallon of petroleum use. Comparing marginal alternatives to average petroleum understates the potential GHG impact.

A simple model of reduced gasoline demand would be to assign the reduction in output from the highest cost producer as illustrated in Figure 2. Displaced petroleum corresponds to the highest cost producer. Absent this petroleum production, the crude oil would remain underground. In practice the source of the crude oil depends on factors such as OPEC production limits, transportation costs, national energy policies, and other factors.

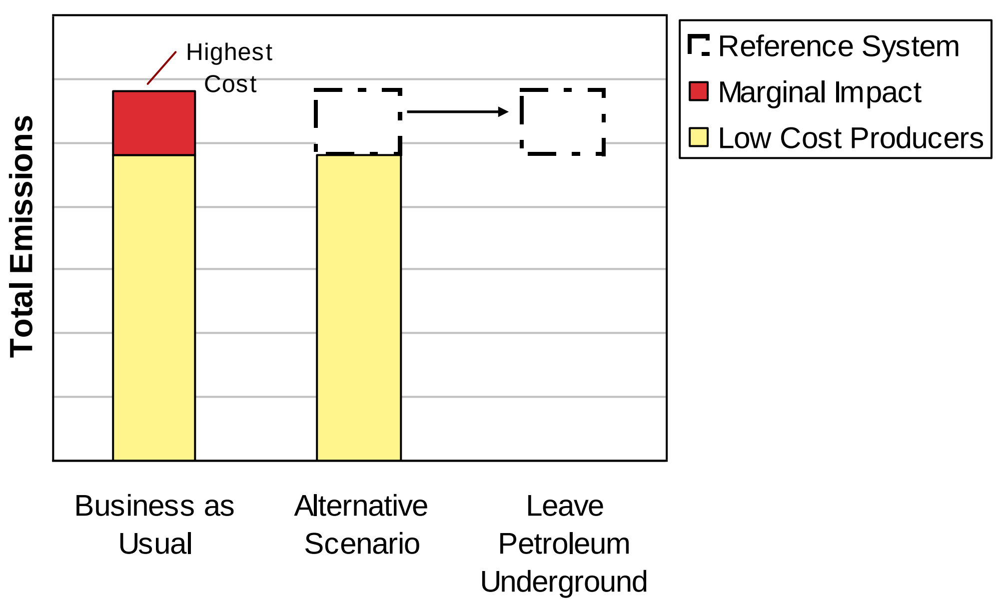


**Figure 2.** Life cycle impacts occur on the margin as shown by ‘business as usual’.

Other analysis techniques could interpret the sources of marginal petroleum. These might include:

- Interviews with traders and market participants to assess capacity limitations and supply patterns
- Oil industry sector models which include supply curves based on extraction and production technology
- Consideration of capacity limits on U.S. refineries and requirements for imports of finished product
- Econometric models that estimate the effect on the U.S. and worldwide economy based on inputs such as the production of competing fuels or fuel economy

Of course considering a broader range of factors in the life cycle of petroleum adds to the complexity and uncertainty of the analysis. Delucchi takes the marginal argument one step further by proposing that all life cycles of fuels should be based on a consequential analysis of their production including the effects on resources and global prices (Delucchi 2008).

In principal, a consequential assessment of a product would determine the marginal energy inputs and related emissions that are the result of production and use of the product. These impacts could include activities far removed from the direct effects. For example the consequential use of natural gas as a process fuel would include the energy required to make up for natural gas consumed from the local gas grid. The source of energy could include:

- More natural gas from existing sources
- Natural gas from LNG
- Reductions in natural gas demand due to price effects
- Switching from natural gas to other fuels due to price effects
- All other indirect and induced price effects that are the result of an increase in natural gas usage including all factors of production in the economy

Marginal petroleum resources correspond to the more expensive and harder to reach barrel of oil. At higher price levels more energy intensive and expensive resources such as heavy oil and stripper wells are brought into production. Some of the sources described in this study would certainly be considered on the margin.

## 2.4. Economic Effects

Economics ultimately determine which petroleum resources are produced on the margin including factors such as production costs, sunk capital, and others. The effect of petroleum production, consumption, and co-products also generates economic effects with resultant GHG emissions. The factors of production associated with petroleum supply and consumption affect the consumption of consumer goods, prices in the economy, and a cascading effect of energy use and emissions. Price effects are largely understood to be the response of the marketplace to a change in supply of goods.

In a theoretically perfect economy, all factors of production respond to the equilibrium of supply and demand. The entire global economy should respond to a change in the supply of a product such as corn or residual oil. World prices should change in response to supply availability affecting all factors of production and economic sectors.

### 2.4.1. Indirect Impacts of Biofuels and Effect on Indirect Petroleum Effects

The indirect effects of biofuel production and use have been incorporated into recent life cycle calculations. Most notably, the effects on land carbon accretion as well as a limited set of other indirect effects of using corn as feedstock for ethanol are part of the RFS and LCFS calculations (EPA; ARB LCFS 2009).

Direct LUC emissions are associated with the clearing of land and land preparation to grow crops for biofuel production and include changes in soil carbon and above ground flora. All of the above ground carbon and a significant fraction of soil carbon are converted to $CO_2$ when land is converted to agricultural production. The second category, indirect or market-mediated LUC, occurs when the production of biofuels displaces some other land use (e.g. grazing for livestock). These effects are extremely difficult to predict or measure with any accuracy, and are highly uncertain due to their indiscriminate and often indiscreet variables.

Indirect LUC has been treated as an economic phenomenon predicted by economic (partial or general) equilibrium models that represent food, fuel, feed, fiber, and livestock markets and their numerous interactions and feedbacks. Results from large-scale economic models, however, depend on a wide range of exogenous variables, such as growth rates, exchange rates, tax policies, and subsidies for dozens of countries.

Indirect land use effects are part of the statutory requirements of the Energy Independence and Security Act (EISA 2007). EPA is currently using the FASOM and FAPRI models to estimate the impact from changes in crop acreage on domestic and international land use. The GTAP model is being used by UC Berkeley and Purdue University to evaluate indirect land use conversion impacts of biofuel production expansion. This effort is used in support of the California LCFS.

While the assessments of LUC for biofuels provide considerable insight into the land use impacts of fuels, these modeling efforts to date have not included all impacts that are directly related to the use of biofuels and include:

- Agricultural inputs associated with indirect crop production (example is given below)
- Direct GHG emissions associated with changes in agricultural commodity transport
- Broad range of consequential economic impacts

Other indirect effects are also difficult to predict and include:

- Non equilibrium prices (in other words: the real world price of goods)
- Effects on petroleum prices
- Shifts in currently markets
- Innovation-based yield and efficiency increases
- Demographic trends

### 2.4.2. Direct and Indirect Effects of Petroleum Production

A working definition of direct and indirect effects of petroleum production produced the groupings in Table 4 of indirect vs. direct effects and depict which are covered in more traditional LCAs and which effects are not (as denoted by the closed vs. open circles).

**Table 4.** Categorization of direct vs. indirect effects of petroleum production.

| | Direct Effects | | | | | | | | | | Indirect Effects | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Petroleum Supply Option** | Oil Exploration | Oil Production | Methane losses, flaring | Oil Refining | Oil and Product Transport | Land Use Conversion | Tailing lakes, $CH_4$ | Vehicle fuel | Exhaust minor species | Material inputs | Refinery Co-products | Macro Economic Effects | Protection of oil supply | Iraq Reconstruction | Indirect land Use [b] |
| Venezuelan Heavy | ⊙ | ⊙ | ⊙ | ⊙ | ◎ | ⊙ | – | ● | ● | ○ | ⊙ | ⊙ | ⊙ | ⊙ | ⊙ |
| Canadian Oil Sands | ● | ◎ | ⊙ | ◎ | ◎ | ⊙ | ⊙ | ● | ● | ⊙ | ⊙ | ⊙ | – | ⊙ | – |
| Iraqi | ⊙ | ⊙ | ⊙ | ◎ | ◎ | – | – | ● | ● | ○ | ⊙ | ⊙ | ⊙ | – | – |
| Nigerian | ⊙ | ⊙ | ⊙ | ◎ | ◎ | – | – | ● | ● | ○ | ⊙ | ⊙ | – | – | – |
| California TEOR | ● | ⊙ | ⊙ | ◎ | ◎ | ⊙ | – | ● | ● | ○ | ⊙ | ⊙ | – | ⊙ | – |
| U.S. Off Shore | ⊙ | ⊙ | ⊙ | ◎ | ◎ | – | – | ● | ● | ⊙ | ⊙ | ⊙ | – | – | – |
| Conventional | ⊙ | ● | ● | ◎ | ◎ | ⊙ | – | ● | ● | ○ | ⊙ | ⊙ | – | – | – |

● Included in traditional[a] fuel life cycle analysis
○ Excluded from traditional fuel life cycle analysis because relative difference among fuels is small
⊙ Not included in traditional full fuel life cycle analyses
◎ Include in traditional fuel life cycle analyses and needs much work
– Not applicable
[a] Delucchi's work on fuel life cycle analysis includes many of the effects in this table or recommends work in these areas
[b] Market effects of petroleum would also include induced effects on land use.

## 2.5. Direct Emissions of Petroleum Use

Table 5 summarizes the direct effects of petroleum production considered for inclusion in this study. These include a review of the inputs for average crude oil production in the U.S. and follow the energy inputs and emissions from well to wheel. The effects of unconventional and marginal resources are also examined. Reference to section numbers is also included.

**Table 5.** Direct GHG Effects Due to Petroleum Usage

| Category | Emission Impact | Report Section |
|---|---|---|
| Average U.S. Crude Oil Production | • GREET inputs based on aggregate statistics<br>• GREET calculations are based on 1 mmBtu of crude oil feedstock to make 1 mmBtu of product (gasoline, diesel, LPG, residual)<br>• Upstream calculations in GREET are intended to reflect bbl of product /bbl of crude | GREET 2.2; 2.7; 3.1 |
| Oil drilling venting and flaring | • Methane leaks from oil wells and associated gas<br>• Flared associated gas | 3.1- 3.3 |
| Exploration and Production | • Drilling<br>• Exploration activities<br>• On-shore and off shore | 3.1-3.3 |
| Oil sands processing | • Energy inputs for tar sands extraction, heating, and hydroprocessing | 3.1.4/3.2/ 3.4.2 |
| Enhanced crude oil recovery | • Gas and oil fired steam generators<br>• Electricity co-product credit | 3.4.1/ 4.1 |
| Heavier crude oil processing | • Hydrogen production<br>• Residual oil production | 3.4 |
| Deeper Refining | • Installation of equipment for more complete conversion<br>• More hydrocracking and energy intensive processes<br>• Lower quality asphalt production | 3.4 |
| Crude and Product Transport | • Marine crude carriers<br>• Smaller cargo capacity effect | 3.5 |
| Vehicle Fuel | • Not addressed in study as depends on fuel economy and gasoline composition (variable) | Not discussed in this report |
| Labor[1] | • Personnel travel, housing, employee food, other goods, and services | Not discussed in this report |
| Oil facility production and material inputs[2] | • Steel, concrete, other materials<br>• Construction equipment<br>• (Note: this category is small and comparable among all fuels)<br>• -- not included in this study. | Comparable among fuel options; not examined in this study but worthy of future study |

1. Emissions associated with labor costs were not examined in this study.
2. Material inputs for vehicles and facilities and recycling were not examined here. The materials for vehicles are essentially identical for all liquid fueled vehicles. Both petroleum and biofuels facilities require material inputs. The analysis of these emissions would require an extensive examination of facility requirements and the time horizon that is applied to fuels.

### Indirect Effects of Petroleum Use

The indirect GHG effects of petroleum use that are outside the scope of the GREET model, include the following high-level categories and are listed in Table 6:

1. Protection of supply
2. Land use and other environmental impacts
3. Market-mediated impacts relating to dependence on, or the price of oil[3]

**Table 6.** Potential Indirect GHG Effects Due to Petroleum Usage.

| Category | Emission Impact | Report Section |
|---|---|---|
| Refinery residual oil production | • Refining crude oil produces more residual oil on the market | 4.1 |
| Protection of supply | | Section 4.3 |
| Emissions from U.S. government military activities in defense of Middle East oil fields | • Gulf War I and II<br>• Naval activity in Persian Gulf<br>• Iraq occupation<br>• Other military activities to be identified from DOE studies<br>• Troop training and preparation<br>• Estimate based on $ expenditures | 4.3 |
| Increased material use (i.e. cement) for war zone reconstruction | • Power plant, building, bridge, road construction<br>• War zone transport of materials | 4.4.1 |
| Oil field fires due to military activities | • Kuwaiti oil fields burned for several weeks after Gulf War I | 4.4.2 |
| Land Use Impacts | | Section 5.0 |
| Tar sands and oil production land impact | • Mining, hydrogen production (in GREET) | 5.2 |
| Road construction | • Road building is catalyst to deforestation destruction | 5.1 |
| Economic Impacts | | Section 4.2 |
| Tar sands use of natural gas for processing | • Pressure on natural gas for power production, shift to more coal imports | 4.2 |
| Price pressures on agricultural commodities from petroleum prices | • Fertilizer, labor, seed, fuel, etc.<br>• Shift from natural gas to coal based fertilizers<br>• Destruction of forest for fuel | 4.2 |
| Price pressures on gasoline with decreased/increased | • Rebound effect | 4.2.2 |

[3] The supply and demand of goods and services respond to the price of oil, thereby inducing economic effects. The economic activities that either depend on petroleum fuels are or otherwise track the price of petroleum would most likely also encounter changes in economic activity and resultant GHG emissions. Agricultural commodities, travel, industrial chemicals, and a variety of goods and services are affected by petroleum prices.

## 2.6. Attribution of Emission to Fuel Production

Attributing emission impacts to fuel production provides a number of methodological challenges, especially for indirect effects. The causality between the indirect effects, categories of emission effects, time horizon and actual petroleum production are subject to a range of interpretations. The readers of this report may not agree with the approach taken here but the exercise of quantifying the effects and presenting a calculation approach is nonetheless valuable as it places a bound on emission impacts there might be considered too vague to quantify.

Attributing indirect GHG emissions to a unit of fuel (e.g. to compute grams $CO_2e$/MJ) requires that we define the quantity of fuel associated with the emissions. Alternatives include:

- All petroleum-based transport fuel used in the U.S. over some number of years
- Transport fuel only from imported oil, over some number of years
- Transport fuel only from oil imported to the U.S. from the specific country or region under consideration over some number of years

Given the global commodity nature of the petroleum market, eliminating U.S. imports from one region, such as the Persian Gulf, would not directly reduce total output from the Persian Gulf, and the related emission impacts. Instead, a change in U.S. demand would affect global supplies, which would theoretically achieve a new equilibrium based on supply and demand. As such, any marginal reduction in U.S. petroleum use may have little immediate impact on protection of supplies (in the case of military) or associated GHG emissions. However, this reality does not necessarily support excluding an examination of the effect.

Table 7 summarizes the approach to attributing emission effects including the time horizon and related petroleum throughput. For the production of marginal resources, the attribution is relatively straightforward and less controversial. The energy inputs and related emissions are attributed to the marginal petroleum resource. In the case of indirect effects both the time horizon and throughput were assumed to provide a parametric basis for expressing the indirect emissions.

**Table 7.** Example Attribution of Fuel Throughput to Emission Sources.

| **Activity** | **Possible Attribution** |
|---|---|
| Process Based Emissions | |
| Heavy oil refining | Per bbl of heavy oil |
| TEOR | Per bbl of TEOR oil |
| Oil sands production | Per bbl of oil sands crude |
| Broader Oil Production Activities | |
| Military activity | 20 years of middle east oil, U.S. Imports |
| Oil field fires | 20 years of middle east oil, U.S. Imports |
| Road based deforestation | 40 years of forest based oil |
| Oil sands deforestation | 20 years of oil sands production |

Studies on military impacts generally consider the attribution question. Different approaches described in Section 1.1 provide estimates of GHG emissions associated with supply protection. We must then allocate these emissions to a quantity of fuel to provide a term with the desired units of g $CO_2$e/MJ.

For protection of petroleum supply, we consider two possible fuel quantities: (a) all transport fuel consumed in the U.S., and (b) all transport fuel produced from oil imported from the Persian Gulf. Table 8 shows U.S. production, imports, and exports of petroleum for the years 2003-2007.

**Table 8.** Total U.S. Petroleum and Transport Fuel Consumption, 2003-2007.

| Category | Billion bbl |
|---|---|
| Production | 9.67 |
| Imports | 18.26 |
| Persian Gulf imports | 4.13 |
| Gulf imports for transport | 2.89 |
| Exports | 0.04 |
| Net consumption | 27.89 |
| Net consumption for transport | 19.52 |

In the past five years (2003-2007), the U.S. imported 4.1 billion barrels of crude oil from the Persian Gulf, out of a total 18.3 billion barrels imported. Since Persian Gulf imports in this period accounted for 15% of total U.S. consumption, the use of the smaller denominator (Persian Gulf imports only as opposed to all imports) increases the "supply protection adder" by a factor of 1/0.15 or 6.7.

An argument can be made that the protection of Persian Gulf oil serves to control the price of all petroleum, not only in the U.S., but in the world. Since oil is a globally traded commodity, the loss of supply anywhere causes the price to rise globally.

Copulos (Copulos 2003) writes:

> *"Why do military threats to the Persian Gulf warrant a military response while threats to other regions do not? One answer is that the magnitude of the Gulf's production and reserves make it uniquely important. Because of this fundamental fact, while losses from other oil producing areas can readily be offset by surge production from the Gulf, the loss of production from the Gulf could not be made up by surge production in other regions."*

Copulos' argument that a loss of production from the Gulf would fundamentally alter the global oil market supports the notion that ongoing military activities are effectively tied to its oil supply. Further, Copulos' (2006) indicates that 50 to75 percent of Middle East military activity is an ongoing requirement to maintain production capacity[4]. The calculations in Section 3.8 assign all of the military activity to the transportation fuels derived from crude oil.

[4] Included in Milton A. Copulos' testimony on the 'Hidden Cost of Oil'-to the United States Committee on Foreign Relations: 2006.

# 3. Direct Petroleum Production Emissions

## 3.1. Exploration, Drilling, and Production

Oil production is typically the first step in a life cycle analysis of petroleum fuels. Oil production covers a range of technologies depending on the reservoir type, extraction technology, and oil field equipment. In addition, oil production also requires exploration to find the oil, which is typically not included in life cycle analyses. This section examines the data on oil exploration, drilling, and production.

### 3.1.1. Conventional Oil Exploration, Drilling, and Production Data

Over the years, oil production has involved progressively more intensive exploration, drilling, and collection activities. Early oil production activities involved identifying oil seeps and drilling relatively shallow wells. Today's oil exploration activities include sophisticated seismic technologies that detect underground (and in deep water) geological formations. Accessing the oil has also become more difficult. For example: Chevron, Devon, and Statoil recently announced a very large oil discovery in the Gulf of Mexico, which could increase U.S. proven reserves of oil by as much as 50%. However, exploring this source of oil would involve drilling 20,000 feet deep (under 7,000 ft of water).

Ideally, data on energy and materials consumed in drilling would be gathered by surveying oil and gas drilling companies. Since such data are not widely available, aggregated data, such as from the Economic Census, provide the data for oil extraction in GREET and some other fuel cycle analyses. In addition to the data on oil and gas extraction from the Economic Census that was used in GREET, there is newer data presented in a document entitled *Crude Petroleum and Natural Gas Extraction*, and there are two other relevant datasets generated by the Economic Census: *Oil and gas well drilling* and *Support activities for oil and gas operations*.

Data from the 1997 Economic Census provides additional information on oil exploration activities as data from the 2002 Census is incomplete (USADC 1999; USADC 1999; USADC 1999). The three datasets compiled by the Economic Census are described below in Table 9.

**Table 9.** Economic Census Datasets.

| Document | Year | Included activities in document |
|---|---|---|
| Drilling oil and gas wells | 1997 | Drilling oil, gas, service wells; oil and gas well drilling directional control; reworking oil and gas wells. |
| Support activities for oil and gas operations | 1997 | Exploration, geophysical exploration; Cementing; Surveying and well logging; Running and pulling casing and rods; Acidizing and chemical treatment; Perforating casing; Installing equipment; Cleaning, bailing, and swabbing wells. |
| Crude petroleum and natural gas extraction | 1997 | Extraction of crude petroleum including lease condensate; Extraction of gas; Extraction of unspecified hydrocarbons. |

Each of these documents contains data on energy used in the listed activities, broken out by type: distillate fuels, residual fuel oils, natural gas, and gasoline. Each also contains dollar values spent on various inputs, including cement, steel, equipment, maintenance, parts, explosives, drilling fluids, and others.

Table 10 below shows inputs by energy type for each type of activity, in J per 100J of crude oil and natural gas produced.

**Table 10.** Energy inputs to oil and gas support, drilling, and extraction (J/100J of crude oil output).

| Input type | Support for oil and gas operations | Drilling of oil and gas wells | Extraction of oil and gas |
|---|---|---|---|
| Diesel and distillate fuel oils | 0.30 | 0.70 | 0.42 |
| Residual fuel oil | 0.23 | 0.44 | 0.15 |
| Gas (natural or manufactured) | 0.05 | 0.02 | 32.42 |
| Gasoline | 0.16 | 0.11 | 0.43 |
| Electricity | 0.16 | 0.03 | 4.00 |
| Other | 0.98 | 0.43 | 0.00 |
| **Percentage energy of prod. oil & gas** | **0.19** | **0.17** | **3.74** |
| Note this compares with 2% in GREET, 2002 data for extraction is 2.5 J/100 J | | | |

The assessment of energy inputs for crude oil production remains elusive even though these activities correspond to some of the largest components of global fuel production.
The values in Table 10 are different for the extraction of oil and gas column than those reported in the GREET model. This is because these data are based on 1997 Economic Census data, which reports much higher natural gas consumption. The amounts consumed in support and drilling are very small, summing to about 0.2% of the energy contained in the produced oil and gas. This can be compared to the energy used in extraction, which is 3.74% for the 1997 data, 2.5% for the 2002 data and 2.0% in the GREET model. Oil field services and drilling are about 10% of the oil production energy inputs.

These data lump oil and gas together: data on energy use are not broken down into energy used to extract oil separately from energy for natural gas extraction. GREET 1.5 documentation (Wang 1999) discusses the breakdown of Census data between oil and gas production to generate the 98% input in the model.

Support and drilling energy fractions are allocated in this table by dividing the amount of energy consumed for support and drilling in 1997 by production in 1997. In reality, the drilling and exploration performed in 1997 are associated with production in future years. How to rigorously address this difficulty is not known. The assumption implicit here is that the situation is at a “steady state” where the drilling in a year serves to offset the depletion in that year. The effect of well depletion, higher energy prices on efficiency, and the introduction of new resources would be worth investigating. Oil companies actually track GHG emissions associated with production and reefing operations. Unfortunately most of the data is proprietary to the oil companies and not presented in a manner that allows for a ready assessment of GHG intensity tied to throughput and production technology. For example, some data is presented as an aggregate of production and refining. The methods used to track emissions also potentially differ from those in the GREET model and a significant effort would be required to provide the data on a consistent basis.

The Census data provides no breakdown for the energy use tables in "Support Activities" between energy used in different activities (e.g. exploration as compared to cementing). Energy inputs associated with these activities could be calculated from cost inputs in the census data. For example, the cost inputs for exploration, cementing, etc are reported. These inputs could be related to the energy required to make the cement and steel providing insight into the drilling and support activities.

Data for specific project or system designs could also be used to develop estimates of the energy required for operating drill rigs, water separation, pumping, storage and other equipment. Case studies in specific projects would be useful to understand the factors that affect oil production energy inputs such as secondary production technologies (water flooding), drill rig throughput, well depth, oil viscosity, and other factors. While such data would not provide a representation of the average, a better understanding of the basis for the aggregate data and ranges among production projects is needed to provide more confidence in the inputs to petroleum life cycle analysis.

The ranges in energy inputs could be broader than the 2% of crude oil energy +2/- 1% cited in the JEC study (Edwards) for marginal resources such as stripper wells. Stripper wells produce less than 10 bbl per day. Despite their small output, about 80% of the 500,000 producing oil wells in the U.S. are classified as stripper wells, which correspond to 19% of U.S. production (NETL year). The equipment requirements, pumping energy, and transportation modes for this oil resource should be examined in detail as these are typically the high cost producers that operate on the margin. With depleted wells, low oil throughputs and transport volumes, the energy inputs would certainly be larger than the average project. A priority in the area of petroleum analysis would be to determine what fraction of stripper wells are represented by the USADC census data.

Arguably, marginal impact best represents the impact of new fuels (Unnasch 2001). Calculating average emissions is interesting from a historical perspective, while marginal sources are affected by the displacement of petroleum due to conservation or the introduction of new fuels. Heavy oil and unconventional oil represent an increasing share of the market as the price of oil rises and increases in oil imports involve transporting fuels from remote locations with more transportation energy inputs.

**Figure 3.** Oil drilling rig.

### 3.1.2. Offshore Oil Production

Offshore oil production involves the exploration, drilling, and production of oil resources under ocean waters. Exploration and production activities include seismic investigations, exploration drilling, and rig operation such as the one shown in Figure 4. No readily available sources of information were found to break out energy inputs between offshore exploration and production or between offshore and onshore production. The differences are difficult to discern because marine vessels are used both in exploration activities and oil rig support activities with no readily available data on energy use. Additional sources of information would include project developers and operators as well as information sites such as RigZone[5].

[5] http://www.rigzone.com

**Figure 4.** Off shore oil rigs can be located close to shore or in deep water.

Energy inputs for off-shore activities are difficult to estimate as the authors have not found aggregate statistics of energy inputs and oil throughput. More interviews with developers or producers would be needed to estimate energy inputs for specific projects.

Off shore oil production can be expected to require more energy inputs than conventional oil production because of the requirements for marine vessel and equipment operation in exploration and rig operation. Extracting oil from deeper wells will also require additional pumping energy.

A coarse estimate of energy inputs and emissions from diesel fueled equipment was based on the rig population and average power rating of rigs, assuming a 20% load factor with sample calculations shown in Appendix A. The GHG emissions correspond to about 1 g $CO_2e$/MJ or 1% of the energy in petroleum. Since this calculation does not represent all of the energy inputs for offshore activity and the inputs are just coarse estimates, it suggests that the marine vessel operation is a relatively small fraction of total oil production energy. The contribution towards oil production is probably less than 1 g $CO_2e$/MJ. The primary sources of emissions are likely to be marine diesel fuel for exploration and production rigs as well as associated gas fuel used to power turbines on production rigs.

### 3.1.3. Thermal Enhanced Oil Recovery

Traditionally, domestic thermal-EOR was fueled with direct combustion of crude oil. This practice ended in the California oil fields in the 1980s due to air quality concerns surrounding the combustion of unrefined crudes with high sulfur and metal content. California thermal-EOR production is fueled almost entirely from natural gas.

The range of energy intensities represented by 5 historical steamflood projects is 0.21 to 0.43 MJ per MJ of incremental crude oil produced. Since these are operating steam-oil ratios, losses in generation, steam condensation in transport lines, and heat conduction outside of the formation are included. More recent Kern River field data illustrates the impact of accounting for co-produced electricity (CDC-DOGGR 2007). In 2006, 92 Mbbl of water as steam was injected into the Kern River field, approximately 73 Mbbl of which were generated in electricity co-generation plants (CDC-DOGGR 2007). Incremental production from steam injection was 30 Mbbl, giving a steam-oil ratio of 3.06. Steam/oil ratios in other fields were over 5 indicating greater energy requirements for oil recovery.

The steam injection rates and fuel use from the DOGGR data allow for the calculation of energy inputs for thermal EOR. For every MJ put into the oilfield as steam, 2 to 3.2 MJ of natural gas was burned, but 0.5 to 1 MJ of electricity was also produced in addition to the steam.

The steam inputs can be converted to the GREET input value of crude oil extraction efficiency as shown in Table 11. The GWI of gasoline is calculated based on the oil production efficiency input to GREET. In the case of CA TEOR, the fuel shares to produce steam are set to 100% natural gas. The GWI of heavy oil with TEOR is also indicated (see Section 3.4.2).

After taking into account a credit for electric power generation, this energy use results in approximately 15 to 28 g$CO_2$eq. per MJ of crude oil produced assuming natural gas is used as the fuel, a significant increase over the 6 g $CO_2$/MJ average value from GREET for crude oil extraction.

The GHG emissions from TEOR are five times as high as the U.S. average calculated in GREET. Since these emissions are calculated based on the process requirements for oil recover rather than oil production statistics reported to the Department of Commerce, the disparity suggests that other types of oil recover should also be examined in further detail. However, the 15 to 28 g/MJ for TECR crude oil is not necessarily inconsistent with a U.S. average of 6 g/MJ because thermal recovery represents less than 5% of U.S. production. More research is necessary to explain any inconsistencies.

**Table 11.** Energy Inputs and GHG Impacts.

| | | | Fuel Cycle GHG Emissions ($g\ CO_2e$/MJ gasoline) | |
|---|---|---|---|---|
| **Crude Oil Type** | **Extraction Efficiency** | **Steam/ oil ratio** | **Crude Oil Extraction** | **WTT + Fuel Carbon** |
| Conventional | 98% | 0 | 7 | 93 |
| TEOR, NG Boiler[1] | 81.6% | 3 | 15 | 105 |
| TEOR, NG Boiler[1] | 73.1% | 5 | 28 | 113 |
| Approximate heavy/light TEOR, co-generation mix[2] | 65.7% | 5 | 20 | 112 |

1. GHG intensity calculated with GREET using default values for conventional crude oil and indicated extraction efficiency and 97% fuel shares for natural gas and 3% fuel shares for electricity for NG boiler case.
2. Total natural gas use for TEOR with cogeneration is higher than the conventional steam generation cases. GHG intensity includes a credit for co-product electric power of 15 g/MJ, reducing the overall GHG intensity.

The co-product electricity can have a significant impact on the life cycle inventory of the crude resource depending on the method used to treat co-products. One approach is to provide a credit for all of the co-product electric power against the appropriate marginal grid mix. The EU WTW analysis has examined different options for crediting electric power and limiting the potential co-product credit (Larivé). The study examined several options for crediting co-product power. Two key recommendations apply here:

- The credit for power generation should be consistent with the amount of steam required for the fuel production process (California TEOR project require lots of steam and the power production is consistent with the steam generation)
- The credit for power generation should be based on the best use of the natural gas feedstock. So, for natural gas based steam generation, a credit should reflect power generation from a combined cycle combustion turbine and NOT the simple cycle turbine used to generate the power

Larivé discusses the difficulty in employing a methodology for co-product analysis if a credit is to be assigned because some impacts are so extensive and the impact of the displaced product is also uncertain. The conclusion is that the method for applying credits needs to be carefully examined in order to avoid situations where the export power dominates the life cycle result without being related to the marginal production of fuel. The examples here represent situations where a significant amount of steam is generated (over 5 Btu for every 10 Btu of crude oil recovered for an extraction efficiency of 66%). However, since the generation of steam is consistent with the requirements for producing oil, the calculation of a co-product credit may still be reasonable.

### 3.1.4. Oil Sands Production

Oil sands are sources of petroleum heavy oil. Oil sands consisted of heavy oil, or bitumen, mixed with sand. Oil sands are mined with large scale equipment. The bitumen is extracted with steam and the sand remnants pumped into tailing pits. Oil sands are also recovered underground using a thermal process. With the Steam Assisted Gravity Drainage (SAGD) process, the bitumen in collected in a network of pipes (See OTS and OSTSEIS web sites).

Bitumen is piped to an upgrader for further refining. Diluent, with the properties of light naphtha, is blended with the bitumen to enable transport to the upgrader. The upgrader produces diluent amounts comparable to the incoming supply, which is returned back to the extraction operation.

Energy requirements include use of diesel in surface mining equipment, electric power for pumping, separation equipment and other utilities, and steam for SAGD operations or separation of bitumen from oil sands. Steam can be produced from conventional steam generators, combustion turbines with cogeneration, or from the combustion of heavy oil residue.

Energy inputs for unconventional oil resources and the processing of heavy oils are higher than those of conventional resources (Bergerson 2006, Brandt 2005, Marano 2001). The GREET model also performs calculations for Canadian oil sands. The GREET model inputs reflect both in-situ and surface mining operations with steam generation from natural gas. The energy inputs for oil sands recovery are typically characterized by the steam/oil ratio. Surface mining equipment, while enormous, results in a smaller share of the total energy inputs (about 3%) than the energy required for thermal recovery of the oil. Steam/oil ratios of 3 are considered typical for SAGD operations, which appear consistent with the GREET model inputs.

Emissions would be higher for projects where the source of energy is bitumen or coke. However, the trend is to use natural gas and not combust heavy oil residue.

The GHG emissions from oil sands operations are reported by oil sands producers in Canada. In addition, several studies have estimated the emissions associated with oil sands production and as well as shale oil. The emissions impact ranges from 15 to 35 g/MJ depending on the study assumptions and the technology. The range of emission estimates are summarized in Appendix A.

Steam production from oil sands operations also result in the production of several hundred MW of electric power. The Alberta grid is very coal intensive so the effect of a co-product credit based on the grid resource mix would represent an apparent GHG savings. However, the use of natural gas effectively eliminates a natural gas resource that could be used for power generation, creating the possible indirect, market-mediated effect of increasing the demand for coal or residual oil for electricity production. This possible indirect effect of oil sands production should be considered closely given the great magnitude of natural gas reserves required to produce petroleum from oil sands. As such, a credit for any co-product power should be selected on a conservative basis (Larivé), and perhaps not until the corollary indirect effects analysis has been conducted. The GREET model provides no co-product electric power credit for oil sands operations.

### 3.1.5. Oil Exploration and Production Recommendations

Considerable efforts have been applied to analyzing the direct emissions associated with exploration and production of petroleum; however, many impacts of petroleum production remain vaguely characterized. The greatest challenge is difficulty in relating data based on surveys and statistics to specific elements of the petroleum industry. Further investigation of the following activates would improve the understanding of petroleum fuels.

The energy inputs and emissions associated with oil production require further analysis to provide a better understanding of the different types of petroleum supply options. GREET model inputs rely on aggregate statistics that are difficult to validate and vary substantially over the two reporting periods that were examined. The data inputs for other life cycle studies are also limited. Petroleum production activities are generally lumped into one category when there are a broad range of production options and technologies[6]. This lack of understanding applies to the fuels that power almost all of our current transportation systems.

The following activities would provide a better understanding of petroleum production emissions:

- Perform an engineering analysis of the energy and GHG emissions associated with different types of oil and oil sands operations (Note several studies are underway)
- Relate oil company reported GHG emissions to life cycle inputs
- Summarize the best available analysis for oil production emissions and present the information to individual oil producers, exploration companies, and others working in the oil production industry

## 3.2. Oil Sands Tailings

Residue from oil sands processing is another source of criteria pollutant and GHG emissions. For mined operations, bitumen is separated from oil at an extraction plant which recovers about 75% of the bitumen. The remaining bitumen/sand mixture is returned to the mine and in some instances is stored in tailing ponds (Figure 5). The environmental impacts of these ponds is the subject of considerable attention and results in environmental impacts other than GHG emissions (www.oilsandswatch.com).

Methane emissions from tailing ponds and peat soils as well as land use impacts are another potential source of GHG emissions associated with oil sands. Residual hydrocarbons from oil extraction operations could degrade to form methane under anaerobic conditions. Tailings ponds that occur on soils with high levels of peat may provide anaerobic conditions that support the decomposition of peat and formation of methane. These effects are being examined by UC Davis and the University of Calgary; thus they were not examined here.

[6] GHGenius has several categories for oil production

Since the global warming potential of methane is 25 times higher than that of $CO_2$, this significant potential source of GHG emissions should be incorporated into the life cycle analysis of petroleum fuels.

**Figure 4.** Oil sands tailing ponds are a potential source of hydrocarbon emissions. Anaerobic conditions in peat soils could accelerate methane production.

### 3.3. Natural Gas Venting and Flaring

When crude oil is brought to the surface from several kilometers below, gas associated with the oil extraction usually comes to the surface as well. If oil is produced in areas of the world which lack gas infrastructure or a nearby gas market, a significant portion of this associated gas may be released into the atmosphere, un-ignited (vented) or ignited (flared). Flaring of gas either as a means of disposal or as a safety measure to relieve well pressure is the most significant source of air emissions from oil and gas installations. Even if continuous flaring ended, occasional burning of small amounts of gas will still be necessary for safety reasons, such as releasing excess pressure.

According to satellite data released by the U.S. National Oceanic and Atmospheric Agency (NOAA), in 2006 oil producing countries and companies burned about 170 billion cubic meters (bcm) of natural gas worldwide or nearly five trillion cubic feet. That's equivalent to 27% of total U.S. natural gas consumption or 5.5% of total global production of natural gas for the year. If the gas had been sold in the United States instead of being flared, the total US market value would have been about $40 billion.

Flaring gas has a global impact on global GHG emissions by adding about 400 million tons of $CO_2$ annually. This is roughly 1.5% of the world's $CO_2$ emissions. In the United States, the amount of gas vented or flared represents a very small portion of the total amount of gas produced. On the other hand, gas flaring in the Middle East and North Africa region is about 50 billion cubic meters annually, which makes it the second largest flaring region in the world after Russia and the Caspian region (approximately 60 bcm). Sub-Saharan Africa flares about 35 bcm, of which 24 bcm are flared on Nigerian oil fields. The amount of gas flared in the Middle East alone (approximately 30 bcm) could feed a 20 million ton per year liquefied natural gas plant.

The distribution of the largest sources of flaring emissions is shown in Figure 6. The flared gas emissions are compared with petroleum production to calculate flared gas emission intensity in Table 12. The flared gas emission intensity, weighted by U.S. oil consumption by country, is also calculated. The calculated value for the U.S. is comparable to the GREET default. However, the weighted mix of overseas producers is 3 times higher than the GREET default for the U.S. and 50% higher than the default that represent average petroleum. Moreover, flared emissions from some countries are 25 times higher than the level of U.S. oil production.

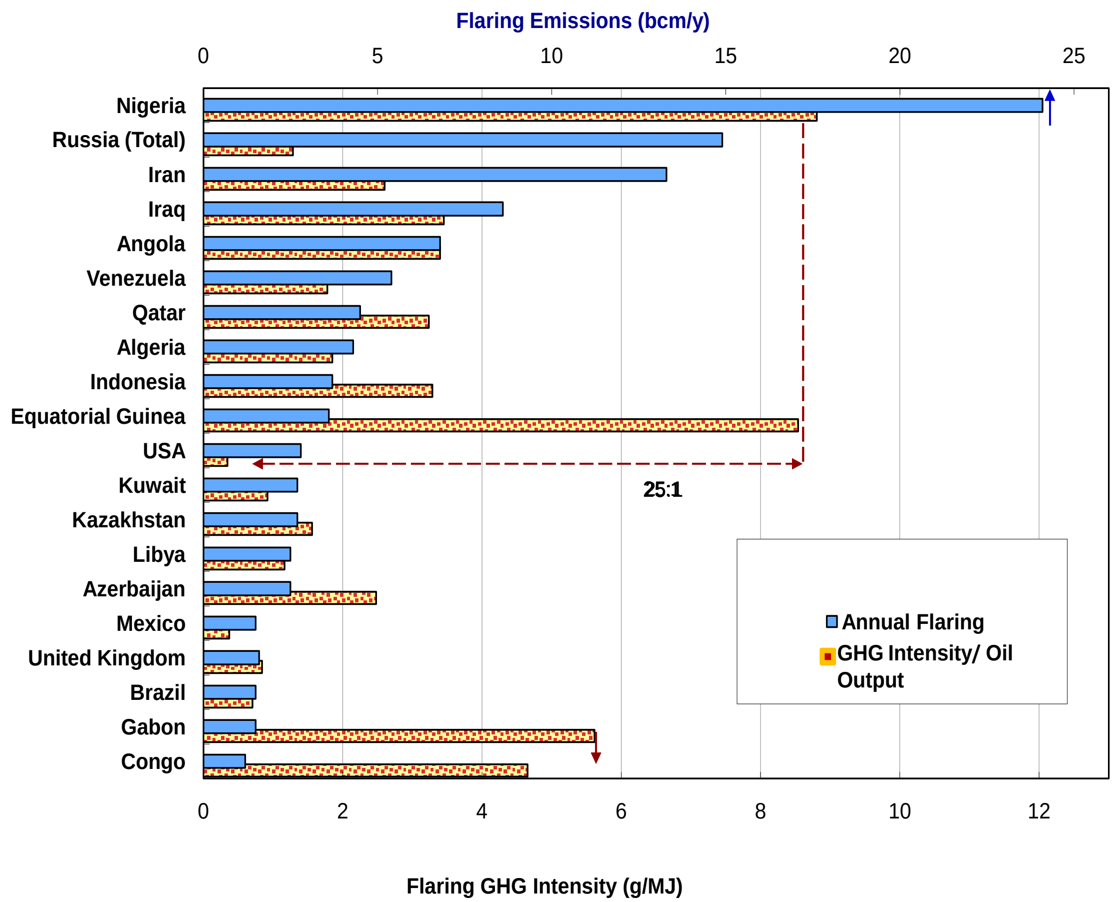


**Figure 5.** Leading countries with flared gas emissions (Source: World Bank, EIA petroleum).

Venting of natural gas is actually a larger GHG source than flared when the warming potential of methane is taken into account. About 5 times as much methane if flared compared with vented but the GWP for methane is 25 times higher than that of $CO_2$ which is the end product for most of the flared gas. Vented gas emissions would also be higher in regions outside the U.S. GREET inputs for vented emissions are based on EIA data for vented gas in the U.S. divided by U.S. petroleum production (Wang 1999). GREET inputs for aggregate venting emissions are based on ANL's assumption that "*flared and vented gas per barrel of imported oil is twice that associated with domestic oil production*".

Interestingly, the aggregate flaring estimate in GREET is comparable to the value calculated here for the Worldbank data even though the data is quite inconsistent in terms of the relative emissions by country. Presumably a number of offsetting parameters result in the serendipitous result. The Worldbank estimates for flaring, up to 400 million tones $CO_2$ annually, are based on satellite observations while the EIA data for the U.S. flaring are based on emission factors and reporting from emission sources. The wide range in flaring data suggests that the emissions associated with natural gas venting are also large. Venting emissions depend both on equipment and operational practices as well as the amount of associated gas produced per barrel of oil. These data are not well reported; so, a high degree of uncertainty should be associated with vented gas emissions.

Vented gas is also a significant source of GHG emissions and the assumption that imported emissions are only twice U.S. levels is likely optimistic given the extensive efforts applied in the U.S. to limit methane losses. Methane venting occurs because of a number of factors. Gas produced with oil production leaks around casings. The extent of such leaks is a function of the amount of gas that is produced with oil as well as the type of oil production equipment. Associated gas may also be vented rather than flared but this practice is not safe. Examining the operational practices of oil fields would provide more insight into venting. However, obtaining access to such information would be challenging.

If the Worldbank data for flared gas represent the relative ratio of overseas to U.S. vented gas, then the factors in GREET are understated and worth examining more carefully as their estimate for $CO_2$ emissions is equivalent to 30% of the EU's gas consumption (www.worldbank.org).

### 3.3.1. Future Trends in Venting and Flaring

Vented and flared gas emissions are a very substantial source of GHG emissions and international efforts are underway to address these emissions. As a first global countermeasure, the Global Gas Flaring Reduction public-private partnership (GGFR) was launched by a World Bank initiative in August 2002. GGFR is a collaboration of governments, state-owned companies and major international oil companies committed to reducing flaring and venting worldwide. The GGFR facilitates and supports national efforts to use currently flared gas by promoting effective regulatory frameworks and tackling the constraints on gas utilization, such as insufficient infrastructure in developing countries and poor access to local and international energy markets, particularly in developing countries.

**Table 12.** Estimate of Natural Gas Flaring in Oil Producing Countries.

| | **Country** | **Flaring (bcm/y)** | **Production (1000 bbl/d)** | **U.S. Consumption** | **Flared m3/bbl** | **g/gal Crude** | **g/MJ Gasoline** |
|---|---|---|---|---|---|---|---|
| 20 | Congo | 1.2 | 222 | 0.4% | 14.8 | 620 | 4.65 |
| 19 | Gabon | 1.5 | 230 | 0.4% | 17.9 | 748 | 5.62 |
| 18 | Brazil | 1.5 | 1833 | 1.0% | 2.2 | 94 | 0.70 |
| 17 | United Kingdom | 1.6 | 1636 | 0.6% | 2.7 | 112 | 0.84 |
| 16 | Mexico | 1.5 | 3477 | 8.3% | 1.2 | 49 | 0.37 |
| 15 | Azerbaijan | 2.5 | 868 | 0.3% | 7.9 | 330 | 2.48 |
| 14 | Libya | 2.5 | 1848 | 0.5% | 3.7 | 155 | 1.16 |
| 13 | Kazakhstan | 2.7 | 1490 | 0% | 5.0 | 208 | 1.56 |
| 12 | Kuwait | 2.7 | 2526 | 1.0% | 2.9 | 123 | 0.92 |
| 11 | USA | 2.8 | 6978 | 40.7% | 1.1 | 46 | 0.35 |
| 10 | Equatorial Guinea | 3.6 | 363 | 0.1% | 27.2 | 1138 | 8.54 |
| 9 | Indonesia | 3.7 | 969 | 0.1% | 10.5 | 438 | 3.29 |
| 8 | Algeria | 4.3 | 2000 | 2.6% | 5.9 | 247 | 1.85 |
| 7 | Qatar | 4.5 | 1197 | 0% | 10.3 | 431 | 3.24 |
| 6 | Venezuela | 5.4 | 2613 | 6.8% | 5.7 | 237 | 1.78 |
| 5 | Angola | 6.8 | 1723 | 2.9% | 10.8 | 453 | 3.40 |
| 4 | Iraq | 8.6 | 2145 | 2.9% | 11.0 | 460 | 3.45 |
| 3 | Iran | 13.3 | 4401 | 0% | 8.3 | 347 | 2.60 |
| 2 | Russia (Total) | 14.9 | 9978 | 0.7% | 4.1 | 171 | 1.29 |
| 1 | Nigeria | 24.1 | 2356 | 6.4% | 28.0 | 1173 | 8.81 |
| | Total | 5.485 | | 75.7% | | | 1.58 |
| Attribution to oil production assuming 90% of flaring is associated with oil production. | | | | | | GREET Defaults | |
| U.S. venting emissions estimated at 43.36 g $CH_4$/mmBtu with average of 69.54 g $CH_4$/mmBtu as GREET default. | | | | | | Flaring: | 0.87 |
| GREET oil processing leaks are inferred by subtracting combustion emissions from total methane from oil production with a default calculation of 15.33 g $CH_4$/mmBtu | | | | | | Venting: | 1.65 |
| Nigerian/U.S. on a $gCO_2e$/MJ basis = 25:1 | | | | | | Oil processing: | 0.36 |

As seen in Table 12 (above), the energy industry must end the flaring of natural gas and the resulting greenhouse gas contribution. Progress has been slow so far but there are signs that efforts to curb the practice will pay off.

In general, there are four different technical solutions for preventing gas flaring:

1. Gas re-injection in oil producing fields to enhance oil recovery or in wet gas fields to maximize liquids recovery (Algeria)
2. Pooling of flare gas resources and construction of a LNG plant with an export terminal (Angola, Regional solution including Equatorial Guinea, Cameroon and Nigeria)
3. Building chemical plants near oil fields to produce liquid fuels like GTL, DME, LPG or Methanol (First pilot studies and plants)
4. Power generation with conventional gas turbines (Russia, Germany), gas engines (Egypt) or micro-turbines

Inexpensive natural gas feedstock is vital to allow methanol, DME, and FTD to compete with petroleum-based fuels. Production of liquid fuels from flared gas can overcome the natural gas distribution infrastructure hurdle in remote locations; such production results in very substantial energy and emissions benefits for produced liquid fuels because of the energy and emission credits from eliminating gas flaring.

Fiscal incentives for reducing gas flaring are often imposed as an economic penalty and put into law by countries making loans or guarantees given by the Worldbank. Likewise, those countries participating in the Clean Development Mechanism (CDM) (eg. carbon credit markets) allow for cost reductions, and therefore environmental benefits, for projects that are verified under the CDM and then sold via the CDM's voluntary mechanism to countries that wish to offset emissions.

The Nigerian Kwale Project, where flare gas is gathered and burned in a 480 MW combined cycle power plant is an example of the Clean Development Mechanism (CDM) at work. The objective under CDM is to offer Carbon Credits to a $CO_2$ polluter (such as someone wishing to offset their airmiles, or a western factory wishing to offset emissions) as a mechanism to offset their $CO_2$ emissions. The ultimate goal is to create an environmentally friendly development in the developing world, such as the Kwale Project, where flaring emissions are reduced as the CH4 and $CO_2$ are captured (and therefore cycled into the system) and marketed to end consumers as gas. However, a clear path needs to be identified for reducing venting and flaring emissions before such emissions from remote locations can be considered on par with more closely controlled production resources in the U.S. (Clean Development Mechanism.2007).

### 3.3.2. Venting and Flaring Recommendations

Aggressive control of these emissions over the next twenty years might substantially reduce overall greenhouse gas emissions. However, there have been no estimates that allow the authors to predict how effective control of these emissions will be in the interim.

With regard to the carbon lifecycle of petroleum, the accuracy of venting emissions should be improved by investigating emission inventories and other studies for the top oil producing regions and relating these emissions to petroleum throughput.

## 3.4. Petroleum Refining

Modern oil refineries such as the one shown in Figure 6 produce a variety of fuels and other co-products. Gasoline, diesel, and kerosene, are the primary transportation fuel products, while LPG and residual oil are also used as fuels for heating, power generation, and transport. Refineries also produce coke and sulfur as co-products and some refineries produce asphalt. Attributing energy inputs to refined products is a challenging exercise complicated by the requirements of producing different products. For example, a crude oil distillation unit separates crude oil into different product streams to enable the refining of all refinery products while an alkylation unit operates to produce only higher-octane components for blending into gasoline. Several approaches have been considered for attributing refinery energy inputs and emissions to fuel products.

**Figure 6.** Modern Oil Refinery.

### 3.4.1. Conventional Petroleum Refining

The method used to assign energy inputs to refined products is challenging because of the complex nature of refineries. Modern oil refineries produce a variety of fuels and other co-products. Gasoline, diesel, and kerosene, are the primary transportation fuel products, while LPG and residual oil are also used as fuels for heating, power generation, and transport. Refineries also produce coke and sulfur as co-products and some refineries produce asphalt. Interestingly, some of the fuels are co-products themselves.

The method for determining “refining efficiency” in GREET effectively allocates energy and emissions to gasoline, diesel, and other products. Oil refineries produce a variety of products using different processes within the refinery to separate product streams, remove sulfur, convert hydrocarbons to high octane components, and many other functions.

Attributing energy inputs to refined products is a challenging exercise complicated by the requirements of producing different products. Several approaches have been considered for attributing refinery energy inputs and emissions to fuel products.

The simplest co-product strategy is to assign all refinery emissions and all of the combusted energy to transportation fuel products in proportion to the energy content of the gasoline, kerosene, and diesel produced. This is essentially the energy allocation method, applied to transportation fuels with the understanding that residual oil and LPG are not the primary products of the refinery, as substitutes with less energy input are readily available.

LPG is a limited transportation fuel as are aviation and marine fuels – at least in the sense that all of these are regulated as mobile sources. This approach does not distinguish between the energy intensity of gasoline or diesel production and more importantly, it does not allow for an assessment of the production of different types of gasoline or diesel fuel as the refinery impacts would be commingled between gasoline and diesel.

Several approaches could be implemented to better understand the attribution of refinery energy inputs to fuel products. Linear programming models or a mass and energy balance based on refinery unit performance data could provide the material balances needed to track the feedstock, fuels, utilities, and emission sources within a refinery.

A linear programming analysis would need to take into account all of the refinery processes, crude oil mix, and economic factors that affect refined petroleum products. A linear programming analysis of refineries would need to be coupled with the impact on the crude oil slate. The effect on imported product would also need to be considered. Such a comprehensive modeling exercise aimed at assessing the impact of reducing gasoline demand has not been undertaken. Such an approach could better relate crude oil composition to fuel specifications, hydrogen requirements, and product yields.

The allocation approach in GREET presents a number of challenges, which tend to understate the GHG emissions of gasoline and diesel fuels associated with refining. The core aspect of the approach is to match EIA data on refinery energy with notional values for the relative energy intensity for gasoline refining. The key challenges with the approach include the following:

- Input requires aggregate data. Not able to examine effect of oil type, API gravity, sulfur, etc.
- Notional gasoline energy intensity does not necessarily apply uniformly to all crude types and refining schemes
- 1 mmBtu of crude oil is assigned to 1 mmBtu of gasoline
- 1 mmBtu of bitumen oil is assigned to 1 mmBtu of gasoline (see Roach presentation)
- Fuel cycle emissions for natural gas are applied only to about one third of the natural gas used to produce hydrogen. (No fuel cycle emissions are applied to the natural gas feeding the hydrogen reformer). This results in a hydrogen carbon intensity that is 6 g $CO_2$e/MJ too low. For fuels that use significant amount of hydrogen, the carbon intensity is under reported by 0.5 g $CO_2$e/MJ (6 g/MJ $\times$0.07 J $H_2$/J product)
- No fuel cycle or WTT emissions are applied to refinery fuel gas (this assumption is not consistent with 1 mmBtu of crude oil assigned to producing 1 mmBtu of gasline). The fuel cycle emissions associated with gasoline refining appear to be under reported by 0.5 g/MJ[7]
- Coal content and coal WTT emissions are assumed for petroleum coke
- Oil sand upgrader burns only natural gas, not fuel gas

Some of the nuances of the GREET approach may be attributed to the allocation scheme. However, on balance, the treatment of oil refining should more closely reflect the process units used to produce products and the impact of crude oil types. Most of the factors identified above affect the upstream energy inputs for the refining, which results correspond to about 10 to 16 g/MJ of GHG emissions in the refining phase. The uncertainty might be another 2 g/MJ (plus an additional 5 to 10 g/MJ for upgrading bitumen or heavy oil). The range in emissions is currently being investigated in several studies.

The relative impact may be small on a per MJ basis; but oil refining is the 3rd largest source of GHG emissions in California, behind fuel combustion and power generation. The GHG emissions of this important industry should be better characterized. Several studies are examining these impacts. The effect of refinery co-products is examined in Section 3.6.

### 3.4.2. Heavy Oil and Oil Sands Upgrading

Sources of heavy crude oil are also growing in market share. Heavy oil has a lower hydrogen to carbon ratio than lighter oil and requires additional hydrogen to upgrade it for refining. Also, higher levels of residual oil may be produced when heavy oil is refined. Unconventional oils are characterized by an API gravity lower than 10 (including oil sands). Oil with an API gravity below 18 would still be considered heavy. These oils are characterized by a high viscosity and typically higher levels of sulfur, nitrogen, metals, and asphaltenes. Many technology providers have developed hydrocracking processes that are

[7] Total energy inputs to refinery is 1/87% or 1.15 J Energy per J Gasoline. 50% of the emissions are assigned to still gas. Since still gas is derived from crude oil with an upstream GHG intensity of 7 to 20 g/MJ, then the upstream GHG impact of still gas would be 0.5 $\times$ 0.15 J/J gasoline $\times$ 7 g/MJ = 0.5 g $CO_2$e/MJ gasoline.

suited for the conversion and upgrading of a variety of heavy oil materials ranging from conventional vacuum residues up to extra-heavy oils and bitumen.

Upgraders can be configured with a variety of processing units including vacuum distillation, hydro cracking, delayed coking, and hydrotreating of naphtha. Upgraders require approximately 1000 scf of hydrogen per bbl of bitumen. The per bbl volume of upgrader product, synthetic crude oil (SCO), depends on the technology used and ranges from 85 to 101 bbl per bbl of bitumen (Roach). Because of the presence of high density naphthenes, aromatics and polar compounds, the H/C ratio is very low compared to the gasoline and diesel fuel products. The increase of the H/C ratio is accomplished by rejecting carbon and adding hydrogen. Carbon rejection processes (such as visbreaking and coking) show very high feedstock flexibility, but generate low quality distillates and significant amounts of coke. Hydrocracking technologies result in a higher yield with more hydrogen consumption but these units are sensitive to feedstock quality.

Current GREET modeling for U.S. refining presumably reflects the impacts of heavy oil from Kern County, California and Venezuela because the GREET inputs are for aggregate U.S. refinery statistics. However, GREET inputs do not readily allow for the calculation of the impact of heavy oil individually.

The key factors affecting the emissions from processing heavy oil are they hydrogen consumption and the conversion yield to fuel products. Hydroprocessing equipment also requires heating, fans, pumps, and other utilities. The impact of processing heavy oils is best addressed by examining refinery flow sheets that are configured for light and heavy oil configurations. Linear programming models could also be used to parametrically examine the effect of oil properties. Such an exercise would need to examine the other impacts, such as the refinery configuration as the LP model generally optimizes on lowest cost. The effect on refinery units would need to be taken into account so that the modeling represents realistic refineries. Absent a study on refining, many references identify the hydrogen requirements for different refinery processes. The hydrogen processing chapter of the Handbook of Petroleum Refining Processes (Meyers) identifies the hydrogen consumption for heavy oil hydrotreating at 400 to 1000 scf/bbl oil and residuum hydrocracking at 1200 to 1600 scf/bbl. The GHG impact of hydrogen consumption alone corresponds to 5 to over 10 g/MJ of GHG emissions. Appendix A shows scoping calculations based on making up the hydrogen in heavy oil to the hydrogen content in lighter oil.

### 3.4.3. Oil Refining Recommendations

Considerable uncertainty persists in the approach to assigning refinery energy inputs and emissions to finished product. Aggregate statistics from EIA reflect refineries in each PADD and allow for the calculation approach used in GREET. However, this approach does not allow for the assessment of differences in crude oil type and composition or the evaluation of different gasoline formulations. The approach for assessing the energy intensity of each petroleum product is also not transparent.

Several studies are examining the effects of crude oil type on the GHG intensity of oil refining and oil sands upgrading. These study results and others should be examined to provide a consistent and transparent basis for attributing refinery emissions to petroleum production. Also, the effect of refining different grades of crude oil and the impacts of co-products needs to be reflected in the petroleum fuel cycle. Such results are expected to be available from several studies in 2009.

## 3.5. Crude and Product Transport

Petroleum transport is a relatively small portion of the fuel cycle GHG emissions when compared to the total for average processes. However, significant quantities of oil and product are moved in smaller vessels. Oil from stripper wells may even be transported by truck. When the crude oil and product are transported in smaller equipment, the relative GHG emissions grow substantially. With a few exceptions, the largest marine crude carriers have a capacity of 250,000 DWT (Figure 7). Smaller tankers are often used to transport finished product in the event of shortages. The effect of fuel transport is illustrated in Table 13.

**Table 13.** Impacts of Crude Oil Transportation Mode.

| Transport Impact | GHG Impact |
|---|---|
| **100% overseas oil** | |
| 1,000,000 to 250,000 DWT oil tanker[a] | 0.17 g/MJ |
| 50,000 DWT product tankers | 1.2 g/MJ |
| **Stripper well operation** | |
| 100 mi truck transport | 0.6 g/MJ |
| [a]GREET default reflect 1,000,000 DWT super tanker. Most crude carriers are close to 200,000 DWT and product tankers can be even smaller. | |

**Figure 7.** Crude Oil Tanker

As noted above, the impact of fuel transportation is generally considered a small portion of the energy inputs and emissions associates with petroleum fuels. However, higher emission impacts occur on the margin as indicated here. The GHG emission intensity rises rapidly with smaller cargo capacity. Also, unconventional fuel transportation practices such as storing crude oil aboard tanker ships at sea (New York Times, January 15, 2009) also leads to higher GHG emissions. In order to better asses these GHG impacts, a better understanding of fuel transport practices and the inventory of crude and product carriers should be developed.

## 3.6. Refinery Co-Products

Oil refineries produce a variety of products using different processes within the refinery to separate product streams, remove sulfur, convert hydrocarbons to higher octane components, and to perform many other functions. Gasoline, diesel, and kerosene, are the primary transportation fuel products, while LPG and residual oil are also used as fuels for heating, power generation, and transport. Refineries also produce coke and sulfur as co-products and some refineries produce asphalt. Interestingly, some of the fuels are co-products themselves.

In general, displacing gasoline with alternative fuels would reduce the imports of crude oil to the U.S. and world wide refinery output and crude oil consumption. Such a shift in crude oil consumption would result in less residual oil and petroleum coke production and the emissions associated with the combustion of these products. The effect of reducing residual oil and coke output would be an increase in prices and a change in consumption patterns. Price increases could result in a reduction in consumption or a shift to other fuels such as coal, natural gas, or renewables (for power generation). These effects are not well characterized by life cycle models.

Arguably, the additional residual oil contributes to the supply of bunker fuel for luxury commerce such as shipping bottled water from Fiji to the U.S. or waffles from Belgium to England and from England to Belgium). The U.S. petroleum economy alone produces 230,000 bbl/y of residual oil and 220,000 bbl/y equivalent of coke along with 3,000,000 bbl/y of gasoline, 540,000 bbl/y of kerosene, and 1500,000 bbl/y of diesel fuel.

Figure 8 shows the imports of petroleum products to the U.S. Most notably the U.S. is a net importer of crude oil and an exporter of coke and residual oil. The mix of U.S. imports is also relevant when calculating distances associated with crude oil transport indicated in Figure 9.

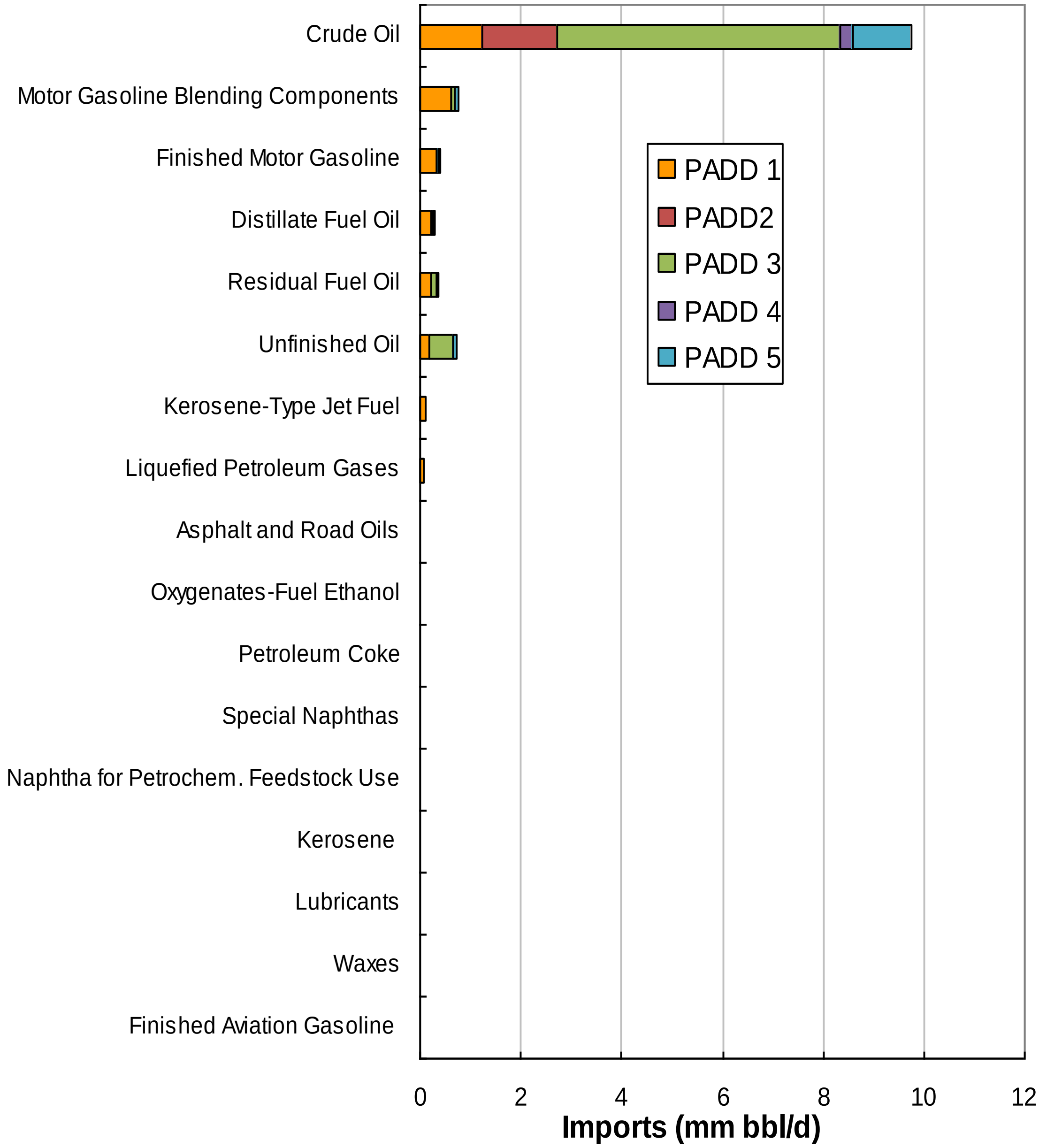


**Figure 8.** Imports of petroleum products to the U.S.

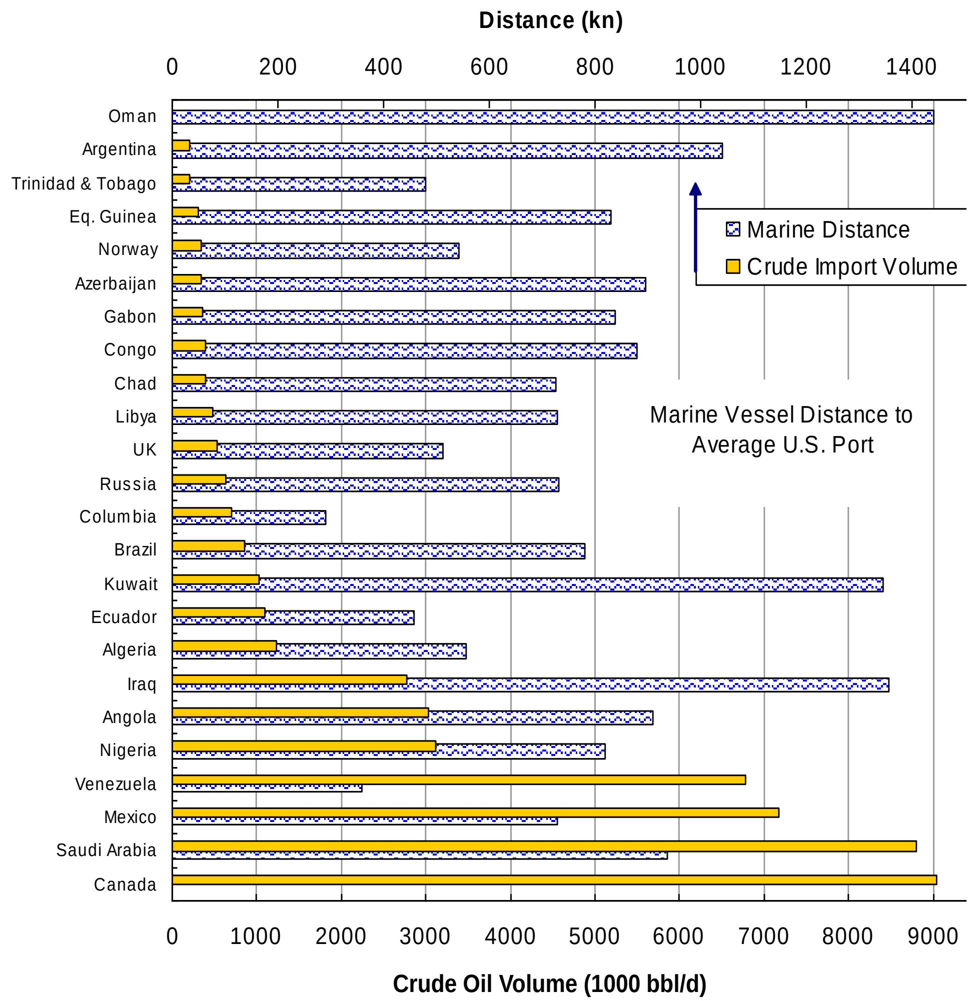


**Figure 9.** Crude oil volume and transport distance.

### 3.6.1. Approach to Refinery Co-products

Attributing energy inputs to refined products is a challenging exercise complicated by the requirements of producing different products. Several approaches have been considered for attributing refinery energy inputs and emissions to fuel products

***GREET Model - Process Based Allocation***

The energy from different refinery units to intermediate product streams is often used in a process based allocation scheme. For example, a crude oil distillation unit separates crude oil into different product streams to enable the refining of all refinery products while an alkylation unit operates to produce only higher-octane components for blending into gasoline. Several studies distinguish between the energy intensity of gasoline or diesel production, which allows for an assessment of the production of different types of gasoline or diesel fuel (Unnasch, Huey et al. 1996; Kadam, Camobreco et al. 1999; Wang 1999; Wang, Lee et al. 2004). Each of these studies estimates the energy consumption and emissions from different refinery units and assigns them to refinery products. In cases where multiple products are produced, the energy inputs and emissions are distributed among the different product streams corresponding to each refinery unit based on its function, energy, volume, or mass of output, and mix of products. The GREET model bases refinery efficiency assumptions on the overall energy input to U.S. refineries and a rule of thumb energy intensity for gasoline. Residual oil and petroleum coke are treated as separate products based on their "refining efficiency".

Residual oil is used as bunker fuel for crude oil transport and as a refinery fuel. Coke is also produced in refineries. The emissions associated with the use of these fuels is included in the life cycle of gasoline in the GREET model. However, the effect of changing residual oil or coke output is not considered in the GREET model because these products are not transportation fuels. Therefore, any emissions associated with processing coke or where coke substitutes for other fuels such as coal are not considered. However, the end use of coke and residual oil is tied directly to crude oil refining and transportation fuel consumption. As world petroleum output grows, demand for coke and residual oil has declined (see Appendix A). However, the effect of bunker fuel and coke that are added to or removed from the market are not considered, and could be a significant source of indirect carbon emissions

### *JEC Study – Refinery Modeling*

The system expansion approach is used by the JEC study. A linear programming analysis of refineries was applied to European refineries with the constraint that the refinery produce only 10% more or less gasoline. The refinery model was constrained to produce no additional products such as residual oil or coke. This analysis shows relatively high refinery efficiency for gasoline production because of the high level of diesel fuel produced in European refineries. Only limited documentation of the refinery modeling is published (Edwards, WTT, volume 3).

### *PwC Study – System Boundary Includes Residual Oil*

A life cycle analysis performed by Price Waterhouse Coopers (PwC) investigated the production of natural gas to liquids (GTL) processes for Shell and Sasol (PwC). This study developed scenarios for total GHG emissions for a reference case and cases where GTL plants displace gasoline, diesel, and other petroleum products. The study frames the system boundary as a constant level of output of transportation fuels and other refinery products. Vehicle miles traveled (fuel), lubricant, bunker fuel, and other products are held constant. The GTL process produces no residual oil.

The system boundary assumptions for the PwC study include a constant level of marine vessel transport for the transport of goods. Since no other fuels are readily substituted for bunker fuel, the study assumes that other uses of residual oil are affected by a reduction in crude oil refining. Essentially, marine vessel transport is considered inelastic or significantly more inelastic than electric power generation where fuel switching is possible. The study then calculates the effect of displacing residual oil from power generation with coal or natural gas fired power. Interestingly, this study makes the most substantial effort to deal with refinery co-products.

### 3.6.2. Residual Oil and Coke Production

For the year 2006, net residual oil and petroleum coke correspond to 9% of net U.S. refinery fuel output as shown in

Table 14. In addition to its use in oil production, transport, and refining, residual oil is used as bunker fuel and for power generation. On a global level, the overall consumption of fuel oil declined 11.7% between 1997 and 2007, lead by the Europe and the Former Soviet Union. Nevertheless the consumption increased by 28.3% in the Middle East and by 16.0% in China.

***Indirect Effects of Refinery Co-Products***

The effect of residual oil and coke production are examined by considering a case where the output of petroleum derived California gasoline blending component is varied by 10%. Calculations for this scenario are shown in Appendix A.

Table 14. **Energy Inputs and Outputs from U.S. Refineries.**

| **Refinery and Blender Net Inputs** | **1000 bbl/d** | **Share (% of Product)** | **Share (% of Fuels)** |
|---|---|---|---|
| Crude | 15,242 | | |
| Pentanes Plus | 184 | | |
| Liquefied Petroleum Gases | | | |
| Other Hydrocarbons/Oxygenates | 444 | | |
| Unfinished oils | 661 | | |
| **Refinery and Blender Net Production** | | | |
| Liquefied petroleum gas | 311 | 1.8% | |
| Finished Motor Gasoline | 8,231 | 47.1% | |
| Finished Aviation Gasoline | 18 | | |
| Kerosene-Type Jet Fuel | 1,481 | 8.7% | |
| Kerosene | 47 | | |
| Distillate Fuel Oil | 4,040 | 23.1% | |
| Residual Fuel Oil | 635 | 3.6% | 4.6% |
| Naphtha for Petro. Feed. Use | 196 | 1.1% | |
| Other Oils for Petro. Feed. Use | 198 | 1.1% | |
| Special Naphthas | 36 | 0.2% | |
| Lubricants | 183 | 1.0% | |
| Waxes | 15 | 0.1% | |
| Marketable petroleum coke | 601 | 3.4% | 4.4% |
| Catalyst petroleum coke | 247 | 1.4% | |
| Asphalt and Road Oil | 506 | 2.9% | |
| Still Gas | 709 | 4.0% | |
| Miscellaneous Products | 71 | 0.4% | |
| Total Liquid Fuels | 15,194 | 86.7% | 78.8% |
| Total Products | 17,526 | | |

Source: EIA, Summarized by ANL (Wang 2007)

The emissions from gasoline fuel combustion as well as fuel cycle emissions (the WTT component from the GREET model) are included here. The WTT emissions include the combustion of some residual oil and petroleum coke in the petroleum fuel cycle. Also shown here are the emissions related to co-product residual oil and coke combustion and their fuel cycle component. The proportional change in these emissions is calculated for a 10% increase or decrease in gasoline production.

The effect of changing gasoline output on emissions associated with residual oil and coke combustion is illustrated in greater detail in 10. Total direct emissions from fuel combustion plus the fuel cycle change from 13.2 Tg/y to 11.9 Tg/y with a net reduction of 1.3 Tg/y corresponding to a reduction in 1.4 billion gallons/year of gasoline production are included in the bar chart in Figure 10. These emissions do not include those associated with oil production and distribution, which are included in the WTT component of gasoline production and included as direct life cycle emissions. The uses of residual oil are also discussed in Appendix A.

The reduction in refinery co-products does not necessarily correspond to a worldwide reduction in GHG emissions. The system boundary assumption for the PwC study implied that bunker fuel prices would increase and marine vessel applications would compete for fuel oil from power generation. Power generators would then switch from firing fuel oil to coal or natural gas.

Assessing the market mitigated impacts of a reduction in residual oil and coke is a more complex question. The regional distribution of refinery co-products, their transport costs, and price elasticities would need to be taking into account. Complicating this analysis is the potential for fuel switching. A reduction in fuel oil for electric power generation could be met with a switch from oil to coal, natural gas or renewables. Efficiency improvements and conservation could also address a shortfall in fuel oil supply. Refineries could also adjust their mix of fuel oil output if prices rise.

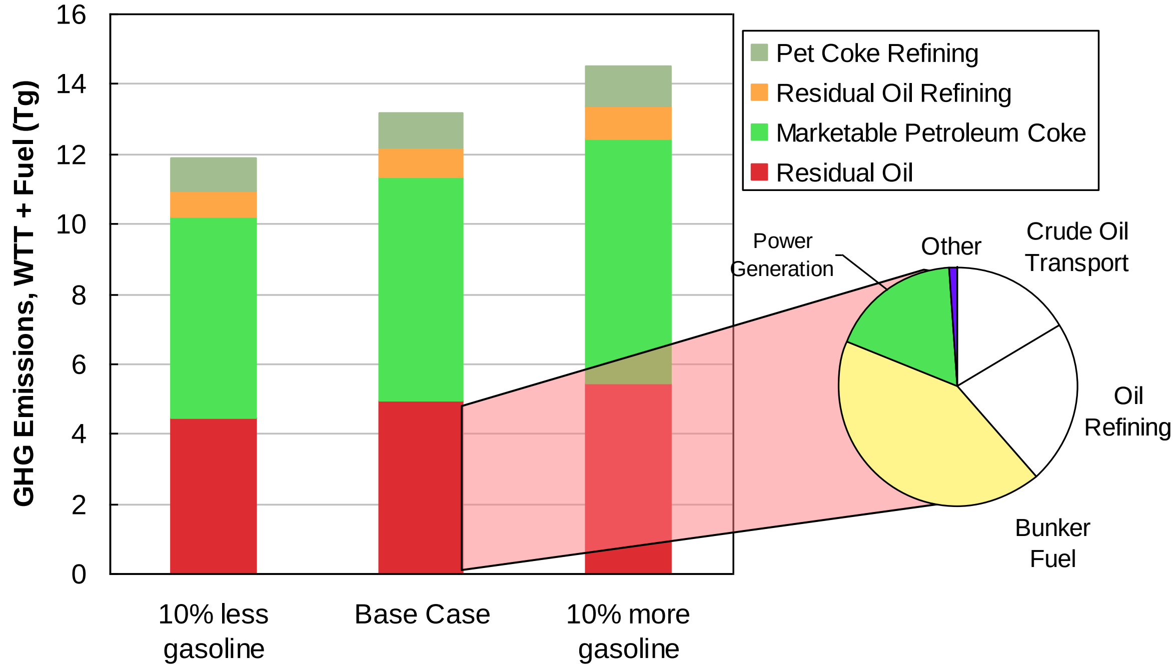


**Figure 10.** Change in residual oil and coke emissions with constant refinery configuration and changing gasoline output.

Source: Life Cycle Associates

These values do not take into account market shifts in fuel usage. Residual oil comprises 4.6% of U.S. refinery output. With a fixed refinery configuration, the amount of residual oil available on the market would drop by this fraction. However, on the margin, imports from more remote locations would be reduced if refinery output drops (or growth is limited). The average distance for imported fuels to California is 7800 miles, which corresponds to about 1.1% of the energy input to gasoline production. Thus reducing gasoline output would reduce the amount of residual oil that is produced, but less residual oil would be used for crude oil transport.

Also shown are the emissions associated with electric power generation from fuel oil. 0.01 MJ of electric power could be produced from the net residual oil available from oil refining. The emissions associated with the same amount of electric power from natural gas, coal, and renewables is also shown as well as the net change in emissions. As indicated, switching from residual oil to natural gas fired power would result in a GHG emission reduction of 1 g $CO_2$e/MJ of gasoline, while emissions would increase if coal were to displace residual oil fired power. Of course conservation or renewable power would reduce emissions further. These emission estimates only bound the effect of residual oil production associated with gasoline production as market forces could result in further fuel switching, conservation, and a mix of these results.

A scoping calculation for the market mitigated effect of refinery co-products is provided in Appendix A. The GHG emissions associated with bunker fuel usage are multiplied by an assumed market share and elasticity factor. The market share assumptions reflect the mix of fuel oil uses that would be displaced and are provided for illustration purposes with a net GHG impact of 2 to 4 g $CO_2$e/MJ of gasoline produced.

### 3.6.3. Refinery Co-product Recommendations

Refining crude oil results in a variety of carbon intensive co-products. The indirect effects of these products are not included in current life cycle analyses of petroleum fuels. The effect of refinery co-products is difficult to predict because they are used in a variety of applications in different locations around the world. The location of refineries, transportation costs, markets for fuels, and options for fuel switching need to be considered. None of the allocation schemes address the effect of residual oil supply on price and demand (and corresponding GHG emissions). The effect of changes in residual oil and petroleum coke combustion are an indirect effect of crude oil production.

Certainly the impact of residual oil and coke are significant on the margins. The production of residual oil had increased with crude oil capacity over the years. With every 1000 bbl of crude oil, 90 bbl equivalent of residual oil and petroleum coke finds a market and results in 49 metric tonnes of GHG emissions.

Since the combustion of refinery coke and residual oil results in as many GHG emissions as 5% of all of the automobiles in the U.S., the subject of refinery co-products deserves greater attention. A scoping calculation presented here indicates a 2 g/MJ impact for refinery co-products. A high estimate would be 4 g $CO_2$ e/MJ with the high range of assumptions regarding displaced co-products.

The fate of co-products should be addressed by assessing both their market mitigated impacts in order to estimate what energy resources are displaced and the effect of other economic factors.

Such an analysis could be accomplished by further examining the trends in heavy oil products. Additional insight might by be developed through economic sector models that reflect the supply and demand of competing materials.

Such sector models could be built into a general equilibrium model or applied separately in more specialized models that focus on petroleum and the energy sector.

## 3.7. Economic Impacts of Petroleum Fuel

The economic impacts of petroleum in principal include all of the effects due to the supply and price of petroleum production and related co-products. Such market-mediated impacts include changes to GHG fluxes (increases or decreases) due to changes in global economic activity in response to changes in the use of petroleum or to the price of petroleum. These effects are challenging to model since the impacts may occur anywhere in the global economy. However, this is also true for recent economic modeling of the price-induced iLUC of biofuels. Calculating the potential economic, market-mediated effects of petroleum would be a comparable expansion of the system boundaries for petroleum fuels. A general model of economic effects is shown in Figure 11.

Market mitigated effects spread through many sectors of the economy. The impact of higher petroleum prices can be seen in the cost of transport of goods and some of their material inputs. Many reports in the news relate a change in the CPI to a change in oil prices. However, higher prices do not necessarily result in higher GHG emissions. Notable exceptions might involve price induced fuel switching. As natural gas prices rise, U.S. produced fertilizer becomes less economic, displacing fertilizer production to more remote locations such as Bolivia or the Middle East[8]. Also, new coal-based ammonia production facilities are being built in China.

Higher petroleum prices can have a much more profound impact in low-income countries where incomes may be only a few dollars per day and the costs of food and cooking fuel represent a significant portion of incomes. The potential outcomes include:

- Political unrest
- Rioting
- Food impacts due to high fertilizer prices and fuel prices for agricultural machinery, as well as higher agricultural commodity prices resulting from higher oil prices, as occurred in 2007-08
- Firewood collection resulting in deforestation

These effects are effectively price-driven but do not lend themselves to economic modeling based on equilibrium or a perfect market. The *price* of petroleum alone may not be the only factor to consider. Supply, distribution constraints, government subsidies, rationing, and other availability factors may produce unanticipated social consequences. However, to the extent that biofuels production or vehicle efficiency improvements mitigates price increases in the petroleum sector, some avoidance of these effects could be attributed to petroleum displacement.

Assessing the economic impact of activities such as energy projects, infrastructure, tax policies, or other activities that could be implemented or permitted by the government are often required by law in many jurisdictions. For example, the California Air Resources Board examines the impacts of its rules, including both the direct effects and indirect economic effects (ARB 2008). Thus, examining the indirect effects of energy and environmental policies is not without precedent.

Economic studies often avoid the use of computational general equilibrium (CGE) models when examining the impacts of fuels recognizing that the nuances of fuel production are lost in the bulk aggregation of CGE models. For example, activities associated with a change in demand for petroleum fuels involve significant changes in fuel transport, residual oil and petroleum coke usage, and related impacts on power generation. Figure 11 illustrates the

[8] While Chile has significant methanol projects based on smaller gas resources from the Antarctic Peninsula, Bolivia, Venezuela, Iran or Saudi Arabia have larger gas resources, in fact, Saudi Arabia has significant investments in fertilizer production.

general scope of the EDRAM model used to assess economic impacts in California.  This modeling approach is used to assess the economic impacts of environmental initiatives such as AB-32 (California's Climate Solutions Act).  This modeling effort also calculates the direct GHG emissions in California but does not attempt to calculate global life cycle emissions.

Econometric models have a limited representation of the segments of the petroleum industry. Typically petroleum production, refining and goods transport would be represented as economic sectors.  Specific sectors are not established for residual oil or petroleum coke markets, tertiary oil production, imported finished product, or marine tanker operation. Input/output models can be more readily modified to take into account the details of a sector associated with fuel production.  Notably, a study for the DOE on hydrogen and the U.S. economy and another study on ethanol and the California economy were based on simpler input/output (I/O) models (RCF, Perez).  These modeling efforts examined the factors of production for different fuel industries and examined the effects on the economy and jobs using "static" I/O parameters that did not take into account the effect of new fuels on fuel prices and other prices.

Nonetheless, CGE models are now being used for predicting carbon emissions associated with the life cycle of fuels.  The FAPRI model applies a CGE approach to determine iLUC associated with biofuels.  The U.S. EPA has used these results to examine biofuels under the Renewable Fuel Standard.  The California ARB is using Purdue's GTAP model for similar calculations.

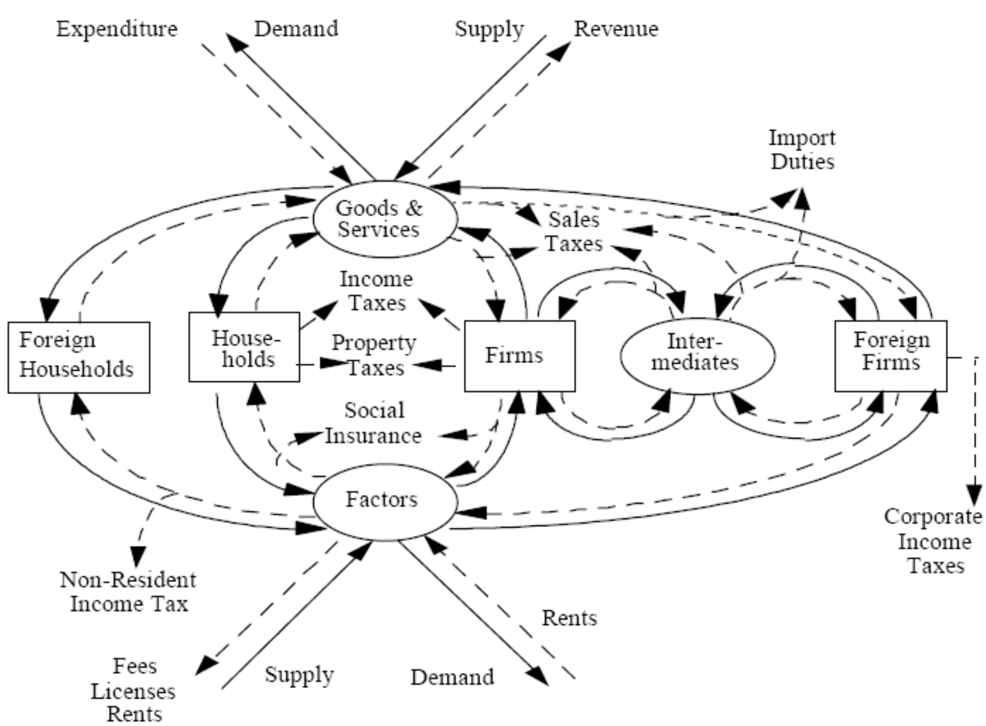


**Figure 11.**  General model representation of economic impacts (Berk).

Such models could also be adapted to track energy inputs and their corresponding life cycle GHG emissions for various sectors associated with petroleum production.

### 3.7.1. Equilibrium Models

Several equilibrium modeling approaches could address some of the economic aspects of petroleum fuels. The following discussion includes two of these models: GTAP and GEMIS.

GTAP

Purdue University's Global Trade Analysis Project (GTAP) is a global network of researchers and policy makers conducting quantitative analysis of international policy issues. Many economic analyses of climate policies have used computable general equilibrium (CGE) models of the global economy. This class of model permits the analysis of policy impacts while considering all the substitutions and exchanges that occur in the global economy.

With its data base covering inputs/outputs and bilateral trade of 57 commodities (and producing industries) and 87 countries/regions, GTAP is able to capture broad sectoral interactions within domestic economies and international trade effects as well.

GTAP has been steadily expanding its capability towards facilitating global economic analyses of GHG emissions abatement. GTAP has successfully integrated global energy data sets – in particular, extended energy balances and energy prices and taxes, compiled by the International Energy Agency (IEA) – into the GTAP input-output tables and bilateral trade data. GTAP could be expanded to include sectors that are specific to the production of petroleum, refining, the end use of co-products, and other aspects of the petroleum economy to address the elasticity of demand questions presented by refinery co-products.

GTAP could be expanded to include sectors of the petroleum industry and related industries. Sectors representing the direct activity associated with oil production, crude oil transport, power generation from petroleum coke, refining and other direct activities could be modeled in sufficient detail to predict indirect effects.

GEMIS

GEMIS 4.4 (Release May 2007) is the acronym for Global Emission Model for Integrated Systems and was developed as a tool for the comparative assessment of environmental effects of energy by Öko-Institut , Germany. Currently, about 10,000 data entries exist in the process database, and some 1,000 products (especially energy carriers with ultimate analysis, and costs).

GEMIS is a life-cycle analysis (LCA) model providing a LCA database and cost-emission analysis system. GEMIS evaluates environmental impacts of energy, material and transport systems, i.e. air emissions, greenhouse gases, solid/liquid wastes, and land use. Environmental indicators are air emissions, greenhouse gases, liquid effluents, solid wastes, land use, and resource use (primary energy and primary material demands). GEMIS can determine the economic costs of scenario options, monetary Input-Output tables can be included for hybrid modeling and costs and labor impacts (direct and indirect) are calculated.

The model can perform complete life-cycle computations for a variety of emissions, and can determine resource use (CER- Cumulated Energy Requirement, CEC- Cumulative Energy Consumption, CMR- Cumulated Material Requirement, land use). It also assesses the results of environmental and cost analyses using an aggregation of emissions into $CO_2$ equivalents, $SO_2$ equivalents, and tropospheric ozone precursor potential (TOPP), and by a calculation of external costs. While GEMIS determines direct and indirect economic effects, emissions are counted only on a direct basis, thus the model would require customization to examine indirect effects.

### 3.7.2. Displacement of Gasoline by Alternatives

A reduction in gasoline output caused by the introduction of competing fuels or changes in vehicle fuel economy can indirectly effect gasoline consumption. Several factors would fall into such indirect effects. First, competition against petroleum would affect supply and price. Subject to production limits by OPEC, more fuel supplies would provide pressure to lower prices. Lower prices provide a stimulus for consumption of all economic goods, which result in an indirect demand on gasoline as well as an induced effect because surplus cash could be used to purchase consumer goods. Lower prices also could result in increased transportation demand. High fuel economy technologies reduce gasoline consumption and provide drivers with near term cash. However, the added cost of technologies such as hybrid vehicles would take away some or all of the savings associated with improved fuel economy. Thus, the economic effect might be a long term net gain to the consumer with more demand for goods and travel. Another effect would be the pocket book impact of high fuel economy. Regardless of the cost of the vehicle, the marginal cost of a trip would be smaller. Hence better fuel economy results in more travel demand.

This rebound effect is the tendency to “take back” potential energy savings from fuel economy improvements as increased travel. These effects have been extensively analyzed in the context of fuel economy improvements and to a lesser extent for fuel substitution (Small 2007). Analyses of this rebound effect examines the interdependencies among miles of travel, fuel economy and price. Strictly speaking, the rebound effect refers to efficiency savings, but a comparable price effect would occur with an introduction of new fuel supplies. Small describes:

“A *Rebound Effect* (also called a *Takeback Effect* or *Offsetting Behavior*) refers to increased consumption that results from actions that increase efficiency and reduce consumer costs. For example, a home insulation program that reduces heat losses by 50% does not usually result in a full 50% reduction in energy consumption, because residents of insulated homes find that they can afford to keep their homes warmer. As a result, they reinvest a portion of potential energy savings on comfort. The difference between the 50% potential energy savings and the actual savings is the Rebound Effect”. Small estimates rebound values ranging from 2.2% and 10.7%, considerably smaller than values typically assumed for policy analysis.

For a 30% improvement in fuel economy, the rebound effect at 2.2% would be 0.66%, thereby resulting in a net improvement of 29.3%. Actually, fuel displacement is not likely to result in such high savings as all of the components of the fuel infrastructure chain adjust to the price of gasoline. A 20 cent per gallon savings would result in a rebound of 0.15% for $3 gasoline. If the effect of fuel economy rebound and new fuels supply are averaged, the aggregate rebound of 0.26% corresponds to a 0.25 g $CO_2$e/MJ increase in GHG emissions.

### 3.7.3. Recommendations on Economic Effects

The effect of petroleum usage on the world economy and its subsequent effects will indirectly result in GHG emissions. Calculating such effects or even defining the assumptions that will ultimately dictate the outcome is a challenging exercise. However, such calculations are frequently undertaken when government projects are considered in order to determine their cost impact. GHG emissions are even estimated using CGE approaches, most recently in the case of biofuels for the CA LCFS. Therefore, considering the magnitude of the GHG emissions associated with petroleum fuels, the calculation of the indirect GHG effects including the appropriate fate or coke, residual oil and the demand for fuel oil for crude transport would be appropriate.

## 3.8. Protection of Petroleum Supply

This section examines the GHG emissions attributable to the protection of oil supplies. There are several challenges to estimating these emissions due incomplete public data on military operations and uncertainty about the percentage of these operations that are attributable to protecting petroleum supply. A variety of approaches discussed in Section 2.6 could be used to attribute these emission impacts to oil production.

The connection between oil and Middle East Military activity is also acknowledged by Government studies focused on the displacement of petroleum. For example, the California Energy Commission AB2076 mentions the connection between petroleum and military activity (Bemis 2003).

> *"Recent disruptions in foreign petroleum and gasoline supplies have harmed the state's economy and led to peaks in gasoline prices. For example, the loss of oil production from Venezuela earlier this year temporarily caused oil prices to rise, leading to high gasoline prices. In addition, in early 2003, concerns about military conflicts in Iraq also resulted in a spike in world oil prices."*

While acknowledging the cost of military conflicts, such studies focus on the direct GHG emissions from petroleum fuels but do not calculate the GHG impact of military activities.

Several analysts have looked at the related issue of the externalized social costs of using petroleum, including military activities to protect oil supplies. The most recent, by Delucchi and Murphy (2008), focuses on the protection of Persian Gulf oil specifically. The authors choose this focus because they believe that "these dwarf the costs of protecting oil from other regions and because it is more difficult to estimate those other costs." They ask, specifically, "If the U.S. highway transportation sector did not use oil, how much would the U.S. federal government reduce its military commitment in the Persian Gulf?"

Delucchi and Murphy proceed in 5 steps:

1. Estimate total annual expenditure to protect U.S. interests in the gulf
2. Allocate a portion of (1) to oil protection. (To account for the vast amount of it)
3. Deduct the cost of defending against worldwide recession related to use of Persian Gulf oil by other countries
4. Estimate the cost of defending investments of U.S. oil producers in the region apart from interests of U.S. consumers
5. Estimate the cost of defending the use of oil in sectors other than highway transport
6.

They estimate that \$6–\$25 billion of the \$27–\$73 billion (2004 dollars) spent annually for military operations in the Persian Gulf is attributable to motor-vehicle use. Since the analysis by Delucchi and Murphy is based on high-level budgetary estimates, conversion of these costs to greenhouse gases would be difficult and highly uncertain.

A bottom-up estimate of the total GHGs associated with the protection of supply would require (at least) the following data:

- Fuel consumed transporting troops and materiel (including fuel itself) and in military actions (jeep, tank, and jet fuel)
- Electricity used to air condition tents in the desert, and the quantity of fuel used to generate that electricity
- Emissions due to heavy equipment manufacture and repair (planes, tanks, jeeps, arms)
- GHGs released by exploding munitions and subsequent fires
- Cement manufacture emissions, fuel, electricity, goods movement for reconstruction
- Oil lost to well fires
- Increased flaring due to disruptions in oil industry practices

Most of the required data is not publicly available or not disaggregated sufficiently for our purposes. Therefore, to estimate the order of magnitude of the effect, we use two distinct approaches based on the data that is available: (1) we use data on total military fuel use to estimate a "protection adder" for the life cycle GHG emissions for transportation fuels; (2) we rely on a report tallying the GHG emissions for the Iraq war to estimate the same "protection adder" based only on the that war.

### 3.8.1. Greenhouse gas estimate for Iraq war

The report "A Climate of War" by Oil Change International, which was published in March of this year, estimates the greenhouse gas costs of the Iraq war (Reisch and Kretzmann 2008). According to this report, the war is responsible for at least 141 million metric tons of $CO_2$ equivalent emissions since March, 2003. The report includes estimates of emissions from fuel-intensive combat, oil well fires and increased gas flaring, increased cement consumption for reconstruction and security, and explosives and chemicals that contribute to global warming. The authors attempted to err on the low side in their estimates, omitting areas where data quality was poor, such as military consumption of GHG-intensive chemicals and the use of bunker fuels for troop and equipment transport to Iraq.

Table 15 shows two possible values for a supply protection adder based on the emissions from the Iraq war. Distributing these emissions across all transport fuels used in the U.S. from 2003-2007 results in about 1 g $CO_2$e/MJ, whereas distributing the emission only across fuels produced from petroleum imported from the Persian Gulf in those same years results in an adder of 6 g $CO_2$e/MJ.

**Table 15.** Protection adder based on Iraq War.

| **Allocation basis** | **Quantity (billion bbl)** | **Protection adder (g $CO_2$e/MJ)** |
|---|---|---|
| All U.S. transport fuels | 19.52 | 0.9 |
| Persian Gulf imports only | 2.89 | 6.0 |

### 3.8.2. Total military fuel use

According to an analysis on the Energy Bulletin website, the U.S. military used an average of about 350,000 barrels of oil per day in the six years from 2001–2006, as shown in Figure 13 (Karbuz 2007). One analyst estimates that 50% of military expenses are for the protection of oil supply (Copulos 2003). We adopt this figure in our analysis.

During this same period, the U.S. consumed 44 billion barrels of petroleum, of which about 70%, or about 31 billion barrels, was for transportation use.[9]

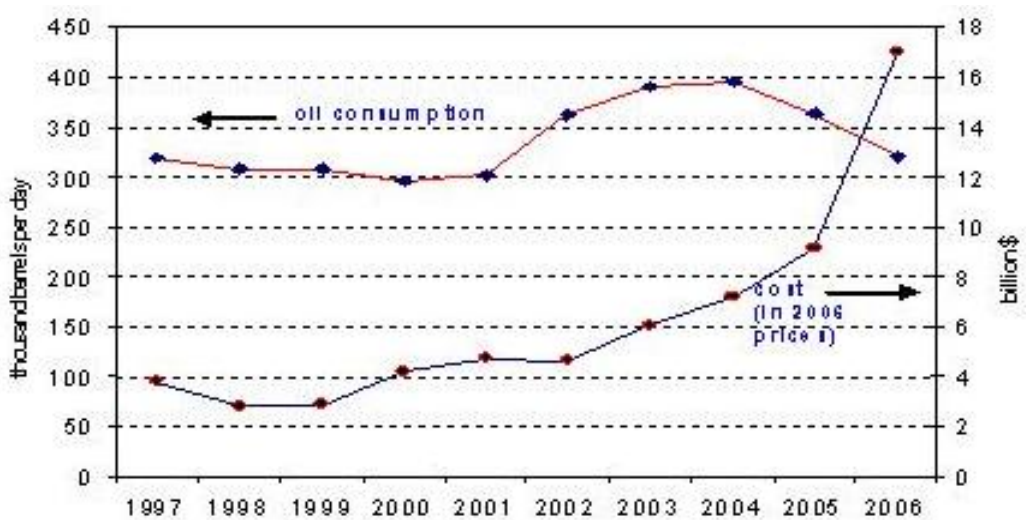


**Figure 12.** The U.S. military oil consumption and costs (Source: Karbuz 2007).

Assuming the military use of petroleum is included in the total given by the EIA, the military accounted for 3.3% of the total U.S. petroleum use in that period. Assuming that (a) the fuel

[9] See http://tonto.eia.doe.gov/dnav/pet/hist/mttupus2a.htm

as used has a life cycle global warming intensity (GWI) of about 95 g $CO_2e$/MJ, (b) about 50% of all military operations are for the protection of oil supply, and (c) the protection of oil supply is attributable to all transport fuels used in the U.S. from 2001-2006, we compute a supply protection adder of about 1.6 g $CO_2e$/MJ. Attributing these emissions only to transport fuels from Persian Gulf oil imported during those years, the adder would be 7.1 $CO_2e$/MJ as shown in Table 16. The $CO_2$ impact of oil field fires in Kuwait is discussed in the following section.

**Table 16.** Protection adder based on Iraq War emissions.

| **Parameter** | | **Iraq War** | **Kuwait Oil Fires** |
|---|---|---|---|
| Daily fuel use | | 350,000 bbl/day | 6,000,000 bbl/day |
| Duration | | 6 years | 2.5 months |
| Assumed attribution | | 50% over | |
| **Allocation basis** | **Crude Oil Throughput (billion bbl)** | **Protection Adder (g $CO_2e$/MJ)** | **Protection Adder (g $CO_2e$/MJ)** |
| **All U.S. transport fuels** | 19.52 | 1.6 | 0.3 |
| **Persian Gulf imports only** | 2.89 | 7.1 | 1.4 |

### 3.8.3. Oil Field Fires

Another effect of Middle Eastern conflict occurred after the first gulf war in 1991. The Kuwaiti oil fires were set by Iraqi military forces retreating from Kuwait. The fires burned for over two months consuming 6 million barrels of crude oil per day (Figure 13). While such an event can be considered a one time occurrence, the GHG emissions correspond to 1.4 g $CO_2$/MJ when assigned to Middle Eastern oil imports over a 20 year period.

**Figure 13.** USAF aircraft fly over Kuwaiti oil fires, set by the retreating Iraqi army during Operation Desert Storm in 1991. Source www.af.mil/photos on www.wikipedia.com

### 3.8.4. Recommendations on Protection of Oil Supply

Addressing the GHG emissions associated with the protection of petroleum supplies presents an ongoing challenge. Relating military activity to oil imports does not lend itself to a straightforward attribution. Nonetheless, the connection between military expenditures, military activity, and imported oil persists. Often government policy studies as well as life cycle comparisons of fuel cite the military impacts of imported oil from an economic perspective while calculations of GHG emissions exclude these effects. If the authors of such studies can make the economic connection between Middle Eastern oil and petroleum, then the GHG emission ought to also be examined as closely.

The calculations in this study show that the emissions are significant for the attribution and time frame assumed in this study. Since the attribution of military activities to petroleum is subjective, a clear path to improving the approach is not apparent.

## 3.9. Iraq Reconstruction

The Iraq war included significant destruction of infrastructure due to bombing, sabotage, neglect, or other war related activities. Infrastructure includes buildings, roads, and bridges whose construction requires energy intensive material inputs including concrete and steel. As described below, cement production is a major component of these efforts.

### 3.9.1. Cement Production

Cement production is a significant contributor to global warming. The U.S. EPA estimates that 3.4% of global $CO_2$ emissions or 829 million metric tons are emitted during the cement production process (Hanle 2004). This section provides an estimate of GHG emissions associated with increased cement demand attributable to the Iraq reconstruction efforts. First, the demand and supply situation for cement used in Iraq's reconstruction effort will be detailed followed by a characterization of the GHG emission factor from the material's production process. Combining cement demand with the emission factor results in the GHG emissions from the reconstruction effort.

***Iraq Cement Demand and Supply:***

A recent article in Arabianbusiness.com asserts that Iraq's current annual cement production from its seventeen production facilities totals between 4 to 5 millions tonnes. An additional 6 million tonnes is imported from Syria and Lebanon to increase current supply to 10 million tonnes (Irish 2008). The supply estimates from this article are relatively consistent with earlier statistical data from USAID, the 2006 U.S. Geological Survey and an article in the San Francisco Chronicle (USAID-Iraq 2007), (Mobbs 2006), (Gilbert February 04, 2006).

Irish points out that Iraq cement demand before the war (before 2003) totaled approximately 10 million tonnes annually (Irish 2008). Current demand is estimated to be much higher in large part due to the reconstruction efforts. The current annual demand is estimated to be 30 million tonnes (Atkin 2008). The cement demand attributable to reconstruction efforts is the difference between current cement demand and the demand before the Iraq war: 20 million tonnes annually. This is a first order approximation that does not take into account other economic parameters such as price elasticity of demand or the influence of UN sanctions imposed prior to the year 2003 on Iraq's cement demand.

### *$CO_2$ Emissions from Cement Production:*

Cement is produced by crushing limestone as well as other minerals such as iron oxides, aluminum, silicon and pyro-processing the materials at high temperatures in special ovens, called kilns (at 1500 ºC). Two basic processes exist: the "wet" process mixes the crushed material with water prior to kiln processing; the more modern "dry" process feeds the material directly to the kiln. Wet processing is more energy intensive and requires about 6 MMBtu/metric tonne; dry processing requires at least 6.9 MMBtu/metric tonne. On average, kiln operation accounts for over 90% of the industry's energy needs (Hanle 2004). Regardless of processing type, the resulting clinker material is cooled, ground, and additives such as gypsum and lime are added to produce either Portland cement or masonry cement, respectively.

### *Emissions factor for Iraq Cement Production:*

The emissions from cement production fall into two categories: process and combustion related emissions. The process emissions are created through the chemical decomposition of calcium carbonate (e.g. from limestone) to calcium oxide and $CO_2$, which results in direct $CO_2$ emissions through the kiln stack (Vanderborght 2001). Note that above it is stated that calcium oxide is put into kilns, whereas here it is limestone. The World Business Council for Sustainable Development (WBCSD) compiled a protocol for assessing $CO_2$ emissions from cement production. For process related emissions, the protocol proposes a default emission factor of 0.525 tonnes $CO_2$/tonne cement.

Combustion emissions are associated with generating the high energy requirements for the kiln operation. World-wide kilns for clinker production are fueled by a variety of energy sources. In the U.S.71% of kiln energy is provided by coal, 12% by petroleum coke, and the rest by waste fuels (tires, garbage) and natural gas. Depending on the production method, the carbon intensity factor of cement produced in the U.S. in 2001 ranged between 0.72 tonnes $CO_2$/tonne to 1.41 tonnes $CO_2$/tonne (process and combustion emissions combined). Worldwide, the average carbon intensity of cement production is on the low end of the U.S. range at 0.83 tonnes $CO_2$/tonne cement produced (OECD/IEA 2007). The lower emission factor is likely due to a higher fraction of natural gas use in other countries (Taylor 2006). Both the U.S. average and the World average cement emission factors, however, are likely not representative of Iraq since all kilns there are fuel oil fired. Fuel oil has a higher emission factor (166 lb/mmBtu) than natural gas (117 lb/mmBtu) but lower than coal (US-EPA Fifth Edition).

Therefore, the combustion related emissions were reassessed using the fuel oil emission factors taking into account that Iraq cement production utilizes about 50% wet and 50% dry processes. The resulting combustion-related emission factor for Iraq cement is 0.577 tonnes $CO_2$/tonne. The process related emissions for Iraq cement are likely close to the WBCSD default value of 0.525 tonnes $CO_2$/tonne. Combining the combustion-related and the process related emission factor for Iraq totals 1.102 tonnes $CO_2$/tonne. This also brings to question the requirement of imported cement and how that is transported.

### 3.9.2. GHG Emissions from Iraq Reconstruction Efforts

The GHG emissions from concrete used for the Iraq reconstruction effort is calculated by multiplying the emission factor (1.102 tonnes $CO_2$/tonne) by the annual cement demand attributable to reconstruction (20 million tons). The resulting annual $CO_2$ emissions from Iraq cement production attributable to reconstruction are 22 million tonnes. Assuming a 5 year reconstruction effort at this level, the total emissions from reconstruction total 110 million tonnes. For reference purposes, the 2010 world $CO_2$ emissions are projected to reach 31.1 billion tonnes (Energy Information Administration, 2008). Annual Iraq reconstruction efforts will correspond to less than 0.1% of worldwide $CO_2$ emissions.

### 3.9.3. Recommendations on Iraq Reconstruction

See Section. 3.8

# 4. Land use and other environmental impacts of petroleum

Petroleum production, transport, and refining require land and therefore have direct land use impacts. Oil transportation also results in local environmental despoliation (e.g. the Niger Delta), as well as oil spills. The GHG emissions associated with direct land use impacts (and in some cases, their cleanup) are likely to be small relative to the total annual flow of oil. Again, it would be appropriate to estimate these impacts to understand the order of magnitude, and to maintain balance with regard to relative carbon LCA boundaries among different fuels

Land use impacts associated with the mining of tar sands, management of tailings, destruction of natural forest, and emissions associated with reforestation are calculated in Section 6.2.

## 4.1. Deforestation following road construction

Road building in forested areas causes relatively small direct emissions, however the roads are often a magnet for subsequent deforesting activities, providing access to previously inaccessible land (NASA Earth Observatory 2008). The cited NASA report notes that:

> *Logging, both legal and illegal, often follows road expansion (and in some cases is the reason for the road expansion). When loggers have harvested an area's valuable timber, they move on. The roads and the logged areas become a magnet for settlers—farmers and ranchers who slash and burn the remaining forest for cropland or cattle pasture, completing the deforestation chain that began with road building.*

Government-sanctioned ("official") roads begin a feedback process that promotes continued expansion of road networks deeper into forested areas. In their review of road building and land use change in the Amazon, Perz, Brilhante et al (2008) note:

> *Distinguishing between official and unofficial roads in the Amazon reveals an important synergy: paving of official roads motivates unofficial road building. Paving raises land values, which provides the incentive to exploit natural resources farther*

*out from official road corridors. This in turn is made possible via construction or extension of unofficial roads, which then generate income that facilitates additional road building.*

Pfaff et al (2007) found evidence of "spatial spillovers" from roads in the Brazilian Amazon. They found that deforestation "rises in the census tracts that lack roads but are in the same county as and within 100 km of a tract with a new paved or unpaved road." Kirby et al (2006) find that "both paved and unpaved roads are key drivers of the deforestation process in the Brazilian Amazon. Proximity to previous clearings, high population densities, low annual rainfall, and long dry seasons also increase the likelihood that a site will be deforested; however, roads are consistently important and are the factors most amenable to policymaking."

Wunder (Wunder 1997) writes:

*More important than the direct clear-felling are the indirect impacts of road construction: It is generally recognized that oil activities "opened up" new agricultural frontiers in the Northern Amazon region by building penetration roads into primary forest areas. Roads thus act as local determinants of deforestation, even in advance of their actual construction (Pichón 1997:71). In the first wave, this gives access to industrial logging operations; second, agricultural squatters follow in order to gradually clear the land by "slash and mulch" methods, [Because of the high humidity in the Ecuadorean Amazon, this is an alternative to the "slash and burn" method that is used e.g. in the Brazilian Amazon (Thapa, Bilsborrow & Murphy 1996:1330).] utilizing it mostly for commercial crops and extensive cattle ranching.*
*…*
*Besides road construction, deforestation "pull factors" provided by the oil sector to agricultural squatters also include the establishment of other local infrastructure and of occasional off-farm employment opportunities. However, about 60% of the population in the Ecuadorean Amazon region's active population works in agriculture (Southgate, Sierra & Brown 1991:1146). In principle, one could therefore question the additional deforestation impact of the oil boom: Maybe road construction directed settlers to specific areas, but in counterfactual terms, the same amount of deforestation might have occurred elsewhere, even without oil production.*

To estimate the extent to which road building for petroleum exploration and production is responsible for deforestation, we must consider the questions:

1. How much road building activity in forested areas is attributable to petroleum exploration and production?
2. How much deforestation is attributable to that road-building? Note that deforestation can occur decades after initial road-building
3. What level of carbon losses are associated with this deforestation? (Deforestation may be thinning or clear-cutting and the carbon density per unit area of forests varies)
4. Over how many years of production should these carbon losses be amortized? This is especially difficult for exploration that does not result in production

We can estimate the upper bound for oil production from rainforest areas from the information in Table 17. The five countries identified as having "substantial" oil operations in rainforest areas produced a total of 3.5 million barrels per day of petroleum in 2004.

**Table 17.** Oil producing countries with rainforests. Primary oil production for most of these countries is offshore. Colombia, Ecuador, Peru, Bolivia, and Nigeria have substantial oil operations in rainforest areas.

| World Rank | Country | Oil Production (bbl/day) | Date of Estimate |
|---|---|---|---|
| 6 | Mexico | 3,460,000 | 2004 |
| 11 | Venezuela | 2,600,000 | 2004 |
| 12 | **Nigeria** | **2,356,000** | 2004 |
| 17 | Brazil | 1,788,000 | 2004 |
| 21 | Angola | 980,000 | 2004 |
| 22 | Indonesia | 971,000 | 2003 |
| 24 | Malaysia | 785,000 | 2004 |
| 30 | **Colombia** | **531,100** | 2004 |
| 32 | **Ecuador** | **523,000** | 2004 |
| 34 | Vietnam | 359,400 | 2004 |
| 35 | Equatorial Guinea | 350,000 | 2004 |
| 39 | Gabon | 264,900 | 2004 |
| 40 | Congo, Rep. of | 227,000 | 2004 |
| 41 | Thailand | 225,000 | 2004 |
| 42 | Brunei | 204,000 | 2003 |
| 49 | **Peru** | **95,500** | 2004 |
| 50 | Cameroon | 94,000 | 2004 |
| 59 | Papua New Guinea | 46,200 | 2004 |
| 63 | **Bolivia** | **39,000** | 2004 |

*Note: The table includes only countries with significant tropical forest. Source: CIA World Factbook (via http://rainforests.mongabay.com/0806.htm).*

We were unable to find much data on road-building for petroleum exploration and production. One report examined this phenomenon along the border between Colombia and Ecuador (Viña, Echavarria et al. 2004), noting that the location of subsequent deforestation depended on what types of activities were pursued. Less deforestation resulted in Colombia, where the deforestation tends to be associated with coca producers, who value remoteness. The authors write:

> *In contrast to the Colombian side of the border, **thousands of kilometers of road construction were sponsored by the Ecuadorian government to support the expansion of petroleum exploration and production**. Large numbers of settlers soon followed the roads and cleared more forests along this new colonization frontier. The Sucumbios province showed the highest rate of population increase in the country,*

*with 6.7% yr-1, during 1974–1990 (29). Although oil production fueled the opening of this frontier in the 1960s, today approx. 60% of the region's economically active population works in agriculture and cattle-raising (30).*
*[Emphasis added.]*

The authors estimate the amount of deforestation associated with road-building based on the proximity of deforestation to the road network, developing estimates of deforestation for areas within 1, 2, and 5 km of roads. Table 18 shows the results for Colombia, and Table 19 shows the results for Ecuador.

**Table 18.** Deforestation on the Colombian Side of the Border.

| **Colombian side** | **1973–85** | **1986–96** |
|---|---|---|
| Total area deforested (ha) | 22,519 | 24,326 |
| Annual rate of deforestation (%) | 1.92% | 2.97% |
| Area deforested within 1 km (%) | 4.61% | 4.14% |
| Area deforested within 2 km (%) | 10.58% | 9.11% |
| Area deforested within 5 km (%) | 30.35% | 26.72% |
| Area deforested within 5 km (ha) | 6,835 | 6,500 |

**Table 19.** Deforestation on the Ecuadorian Side of the Border.

| **Ecuadorian side** | **1973–85** | **1986–96** |
|---|---|---|
| Total area deforested (ha) | 21,167 | 14,911 |
| Annual rate of deforestation (%) | 1.17% | 1.02% |
| Area deforested within 1 km (%) | 55.68% | 42.87% |
| Area deforested within 2 km (%) | 71.84% | 61.83% |
| Area deforested within 5 km (%) | 92.61% | 87.90% |
| Area deforested within 5 km (ha) | 19,603 | 13,107 |

If we assume that all deforestation within 5 km of roads built for petroleum exploration and production in Ecuador is attributable to those roads during the two time periods examined, this amounts to of 32,710 hectares of deforestation. Using the carbon loss factor for Latin American rainforests from (Searchinger, Heimlich et al. 2008) (422 Mg $CO_2$/ha) this deforestation would resulted in the release of approximately 14 Tg $CO_2$.

Ecuador produced about 2.3 billion barrels of oil from 1973 to 1996, and about 3.9 billion barrels between 1973 and 2006.[10] Table 20 shows that if the emissions calculated above are allocated to the 1973-1996 period, the LUC adder would be approximately 1 g $CO_2$/MJ; if the 1973-2006 production is used, the adder drops to 0.6 g $CO_2$/MJ for Ecuadorian oil. This study did not examine trends in road building or the subsequent effects of existing indirect land conversion. The calculation of the LUC adders suggests an overall magnitude of the effect.

[10] http://www.petroecuador.com.ec/idc/groups/public/documents/peh_docsusogeneral/002276.pdf

**Table 20.** Ecuadorian oil production and possible LUC adders.

| Ecuadorian Side | 1973–1996 | 1973–2006 |
|---|---|---|
| Oil production (billion bbl) | 2.3 | 3.9 |
| Deforestation adder | 1.0 | 0.6 |

Obviously, other reasonable assumptions could be made. For example if smaller or larger fractions of the deforestation are attributed to petroleum, or if a smaller or larger buffer is used, the adder will be increase or decrease accordingly. We were unable to find any comparable analyses for other regions.

## 4.2. Tar Sands Production and Other Land Use

Surface mining techniques disturb much more surface area than in situ operations. From an ecological point of view, one of the biggest land use impacts is the fragmentation of land. Therefore, surface area is less important than the linear distance within a given area. There are currently over 100,000 km of roads associated with oil sands production (Bergerson). These activities would have negative effects on many species including caribou and birds (Oil Sands Watch). And the forest clearing or development that occurs as a result of road building may be an appropriate adder to the carbon lifecycle score for tar sands petroleum.

Other oil production activities results in lesser degrees of land disturbance due both the smaller footprint of the oil production activities and they type of land involved. Off shore oil production results in limited disruption of terrestrial vegetation and oil production in desert and arid areas would have a limited impact on the carbon uptake from biota.

In addition to the calculations for tropical forests presented here, others are currently performing an analysis of the land use conversion emissions associated with Canadian oil sands as well as California offshore oil production.

## 4.3. Land Use Recommendations

A variety of direct land use impacts correspond to the production of petroleum fuels. Oil production activities associated with tropical forests result in GHG emissions that may be over 0.5 g/MJ. This GHG intensity is greater than many of the emission sources calculated in the GREET model to great precision but omitted from all major full fuel cycle studies. While the factors that contribute to GHG emissions are uncertain (soil carbon disturbance, fate of above ground biota, etc.); such emissions do, however, appear quantifiable and should be included in life cycle calculations.

Many factors associated with petroleum fuels could indirectly affect how land is used. Even though factors such as social changes, demographic shifts, political unrest, and other behavioral factors do not lend themselves to a straightforward model or calculation, such effects should be examined.

**Table 21.** Summary of GHG Emissions for Different Crude Oil Production Scenarios ($g/CO_2e/MJ$).

| Scenario | Vehicle | Production | Venting and Flaring | Transport | Refining | Protection of Supply | Heavy Co-products | Land Impacts | Rebound |
|---|---|---|---|---|---|---|---|---|---|
| Average Conventional Petroleum | 74.0 | 3 | 2.5 | 1.7 | 12 | | 2.0 | | |
| U.S. Off Shore | 74.0 | 3.9 | 2.5 | 0.8 | 12 | | 2.0 | | -0.2 |
| California TEOR | 74.0 | 14.7 | 0.63 | 0.7 | 13 | | 3.0 | | -0.2 |
| Nigerian Crude Oil | 74.0 | 8.9 | 15.4 | 1.6 | 12 | | 2.0 | | -0.2 |
| Iraqi Light Crude | 74.0 | 12 | 5.9 | 3.0 | 12 | 8.8 | 2.0 | | -0.2 |
| Canadian Oil Sands | 74.0 | 19 | 2.5 | 1.8 | 11.2 | | 1.0 | 1 | -0.2 |
| Venezuelan Heavy Crude | 74.0 | 3 | 2.5 | 1.6 | 20.6 | | 4.0 | 0.59 | -0.2 |

Vehicle emissions include fuel carbon plus exhaust methane and $N_2O$
Refining emissions are based on GREET inputs and allocation approach. The effect of co-products is estimated separately. The overall calculation of both oil production and refining requires further examination.
Land use impact for Canadian Oil sands is a provisional estimate. Others are examining these impacts in detail.

## 5. Impact of Cumulative Additional Effects on Life Cycle Assessment

The direct and potential indirect GHG emission impacts associated with the production of petroleum fuels is shown in Table 21. The different emission impacts are grouped by petroleum supply options with the total presented in Figure 14. The supply options represent case studies that are affected by factors such as the protection of petroleum supply, heavy oil processing, or high venting emissions. Other scenarios could also be selected and these cases are not intended to convey any sort of throughput weighted result.

The energy inputs and emissions for producing petroleum fuels remain uncertain, at least for fuels on the margin. It is not clear how data on oil production relate to the mix of secondary and tertiary recovery options. The methods used to estimate GHG emissions from oil refining are not well developed for examining the effect of heavy oil or high API gravity. Many other uncertainties also exist in the oil production chain. Venting and flaring emissions add considerably to the GHG impact from Middle Eastern and Nigerian sources.

Petroleum production also results in a variety of indirect effects. Most notably, about 7% of the barrel of oil is heavy products and coke. Reducing petroleum production would reduce the output of these products and the world economy would need to adjust. Perhaps energy consumers would respond with the use of more coal but demand rationing, efficiency improvements as well as a switch to natural gas and renewables are also options. Clearly, more analysis is needed.

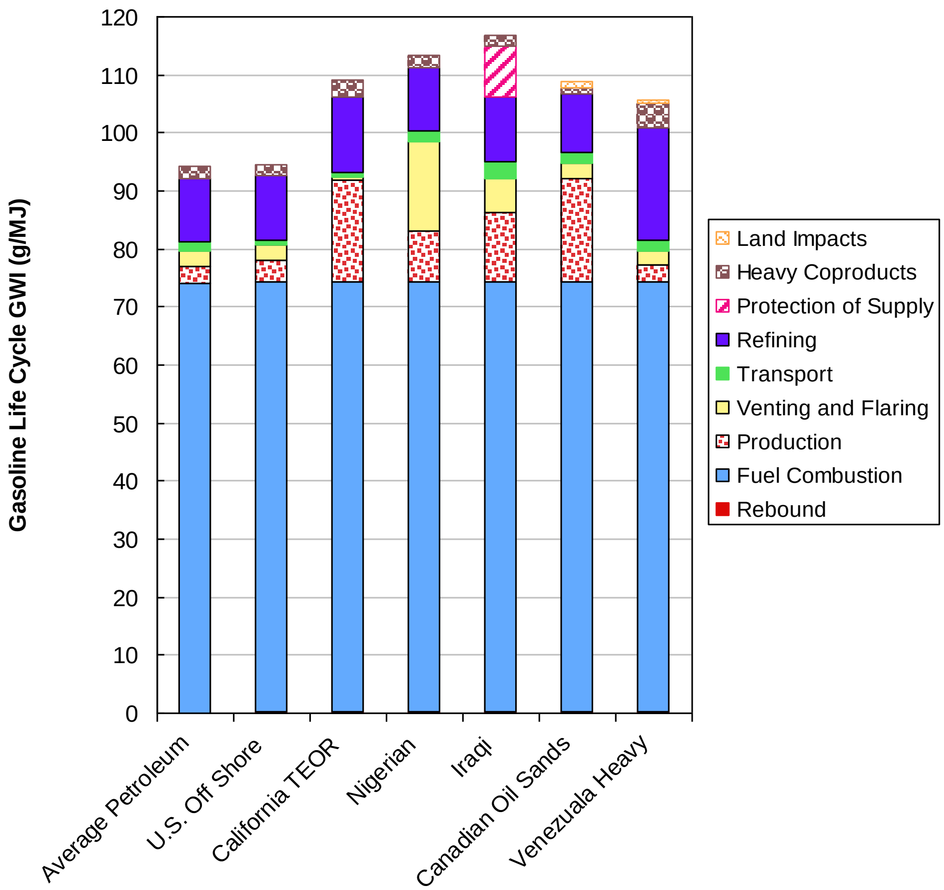


**Figure 14.** Summary of GHG Emissions for Different Crude Oil Production Scenarios.

Finally, petroleum production is associated with activities such as military operations in the Middle East. The GHG impact of these operations is considerable when U.S. activities are attributed to U.S. imports. While the 1% reduction in fuel use will not result in a 1% reduction in Middle East military activity, the overall relationship must be taken into account when assessing the impact of petroleum fuels.

The comparison of so many petroleum options that are a significant fraction of U.S. consumption with emissions higher than the currently used average raises the question: Is the average value correct?

The U.S. average value reflects conventional oil production and does not include Canadian oil sands. The contribution of Canadian oil sands is a feature in the GREET model that is readily calculated. Emissions associated with heavy oil production are embedded in the calculation of the average. This subject requires more research. The emission estimate associated with overseas venting and flaring appears optimistic with the assumption that they are two times the U.S. value.

## 5.1. Uncertainties

The energy inputs and emissions associated with petroleum fuel production result in considerable uncertainty, far more than attributed to the average. Uncertainties in the oil production data, refinery allocation, and the treatment of co-products indicate at least a 5% uncertainty for the average oil production. Figure 15 illustrates the total GHG emissions and estimated uncertainty (on an additive basis) for each of the petroleum pathways examined here. Significant ranges in emissions are related to the following:

- Overseas vented natural gas
- Oil sands processing technology
- Treatment of co-product electricity from cogeneration
- Method used to determine refinery emissions
- Treatment of residual oil and coke co-products

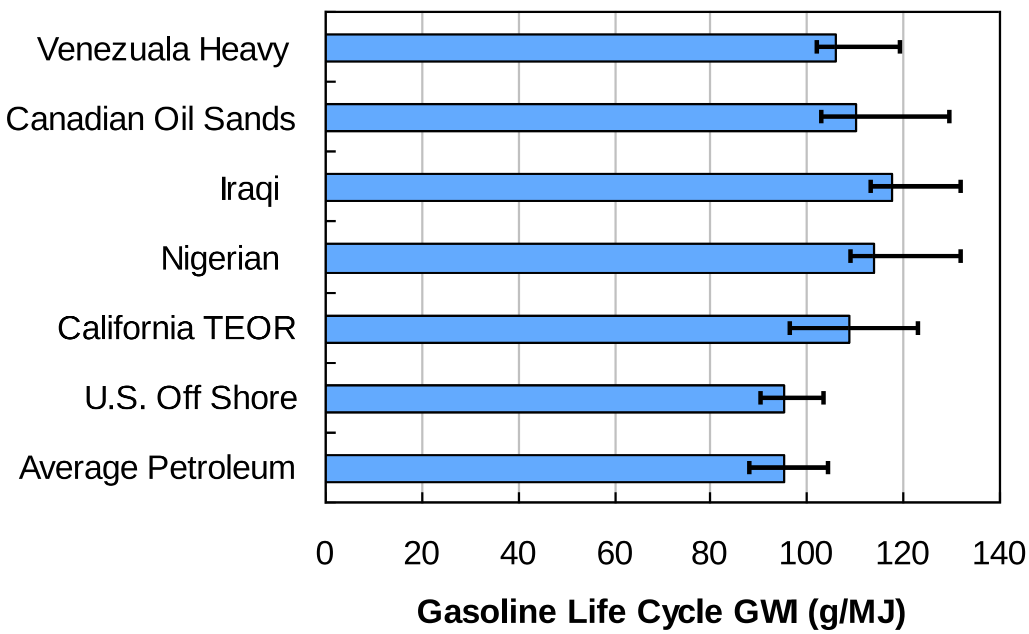


**Figure 15.** Range in GHG emissions for petroleum production scenarios.

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# Appendix

Appendix A provides the reader with additional details about related issues which would have hindered a fluent reading of the main part of this report but, nevertheless, are important for the overall analysis.

## A.1. Estimate of Oil Well Pumping Energy

A coarse estimate of the pumping requirement for oil production is presented in Table A.1. The pumping energy required to raise crude oil from a depth of 10,000 feet is about 1% of the energy associated with the oil or about 1 g $CO_2$e/MJ. All of the inputs are rough estimates, so this calculation merely shows that the energy inputs for rig operations is within the range of estimates for oil production. Additional data would be needed from individual production projects or equipment configurations to provide a more accurate estimate of the energy inputs for oil production. Another way to approach the calculation of pumping energy would be to investigate the engine capacity and fuel use for drill rigs and related equipment. For example, the power requirements for drill rigs range from 1000 to 3000 hp in an introductory book to petroleum from the 1980s (Berger).

**Table A.1.** Oil Well Pumping Energy Calculations.

| | | |
|---|---|---|
| Deep Well Pumping Energy | | |
| 5,000 | ft water | |
| 5,000 | ft below ocean floor | |
| 3,048 | m total head | |
| 9.8 | $m/s^2$ gravitational constant | |
| 1.5 | friction factor | |
| 800 | $kg/m^3$ density | |
| 35,844,480 | N-m/m3 oil, pump work | |
| 80% | pump efficiency | |
| 30% | Pump motor efficiency | |
| 22 | MJ/kg oil | Fuel oil LHV |
| 17,600 | $MJ/m^3$ oil | |
| 0.0085 | MJ Pumping energy per MJ oil | |
| 0.81 | g/MJ | For diesel fueled pumping |
| Drill Rig Engine Power | | |
| 10,000 | bbl/d | drill rig capacity, assumed |
| 1,260,000,000 | g fuel/d | oil density x capacity |
| 3,000 | hp | engine power, 20,000 ft well |
| 200 | g/bhp-h | bsfc, diesel engine |
| 14,400,000 | g fuel/d | fuel use |
| 1.1% | | Engine fuel/Oil production |

Source: (Berger 1981)[11]

[11] (Berger 1981), Modern Petroleum: A Basic Primer of the Industry (2nd edition), Bill D Berger, Kenneth E. Anderson, 1981.

These calculations could be illustrated with any range of assumptions so the key point of the analysis is to demonstrate that pumping energy is within the 2 to 4% of energy required for petroleum production with the possible exception for small stripper wells.

Oil producers could provide project specific data to help provide a better understanding of the range in energy inputs for oil projects. The uncertain use of such data for regulatory purposes would inhibit such an exercise. However, many oil producers already provide GHG emission inventory data for corporate and government reporting requirements. Another approach could be to examine engineering designs for oil production projects and relate all of the process requirements and throughput into an emission intensity calculation.

## A.2. Offshore oil production Energy Inputs and Emissions

Key points include:

- The growing trend is to go deeper
- Difficult to predict
- Calculations are shown in Table A.2

**Table A.2** Estimated Energy Inputs and Emissions from U.S. Offshore Oil Activities.

| | | |
|---|---|---|
| Off Shore Rig Activity | | |
| 40000 | hp engines | Exploration rig power |
| 30% | duty factor | |
| 24 | h/day | |
| 160 | g/bhph | engine fuel consumption |
| 3300 | g/gal | fuel density |
| 800 | rigs | |
| Off Shore Oil Production | | |
| 27 | Mbbl/d | Offshore oil capacity |
| 1,134,000,000 | gal/d | Offshore oil production |
| Off Shore Energy Use and GHG Emissions | | |
| 11,170,909 | gal/d | Engine Fuel Use |
| 0.0099 | J diesel energy/J product | |
| 95 | g/MJ | Diesel GHG factor |
| 0.94 | g/MJ | Off Shore E&P |

## Heavy Oil Refining

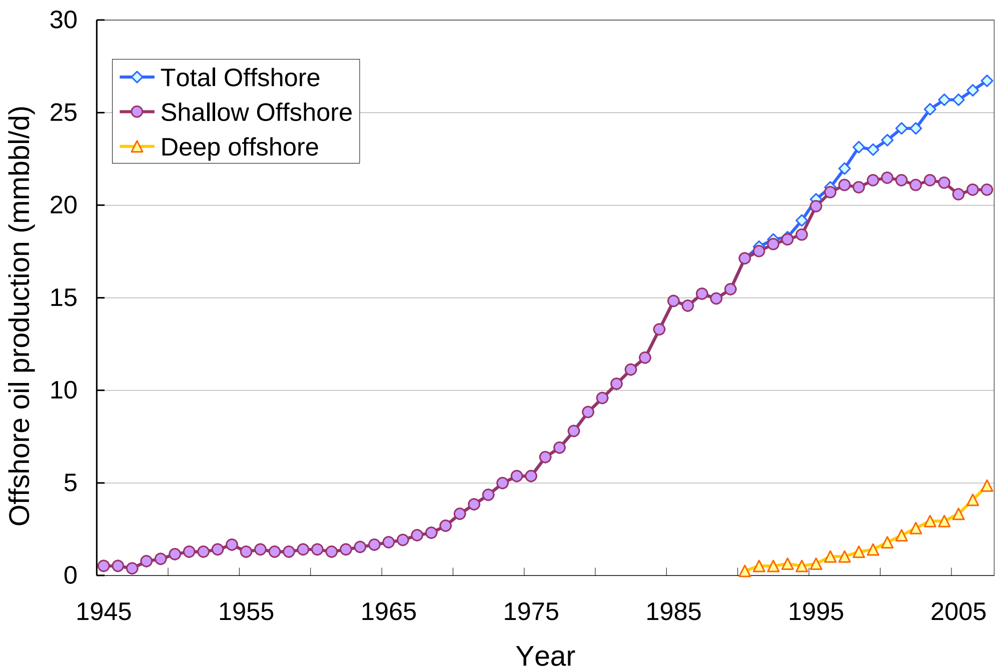
Table 20 calculates the hydrogen requirements and assumed effect on gasoline production emissions based on the hydrogen and carbon content of the feedstock oil. At a minimum, sufficient hydrogen would be needed to make up for the hydrogen deficit in the heavy oil. The oil compositions are based on data in the Fuel Oil Manual (Schmidt). These simple calculations show that the hydrogen demand alone results in 6 to 9 g/MJ of GHG emissions based on a hydrogen production-GHG factor of 95 g/MJ. Adding 25% for process heat and utilities increases the effect of heavy oil processing to 8 to 12 g/MJ. These calculations also indicate the magnitude of the emissions impact and more accurate values should be based on modeling refinery and upgrader configurations.

**Table 20.** Calculation of GHG Emissions Associated with Hydrogen Deficit in Heavy Oil.

| Crude Oil Type | Conventional Crude Oil | Heavy Crude Oil | Light Heavy Oil | Units |
|---|---|---|---|---|
| API Gravity | 27 | 10 | 16 | |
| H content | 11.89% | 10% | 1.9% | |
| H/C, mole ratio | 1.63 | 1.34 | 1.44 | |
| Mol Ratio Difference | | 0.29 | 0.19 | |
| | | 0.02436 | 0.01596 | kg $H_2$/kg C |
| | | 0.00245 | 0.00245 | kg/scf H2 |
| | | 9.94 | 6.51 | scf H2/kg C |
| | | 3333 | 3333 | g/gal |
| | 86.8% | 88.6% | 88.0% | Oil Carbon Content |
| | | 124028 | 123188 | g C/bbl |
| | | 1233 | 802 | scf H2/bbl |
| | | 80% | 80% | yield |
| | | 1541 | 1003 | scf H2/bbl gasoline |
| | | 0.090 | 0.059 | kg H2/gal gasoline |
| | | 0.091 | 0.059 | % gasoline energy |
| | | 8.6 | 5.6 | g GHG/MJ |

Global offshore oil production in 2007 was approximately 27 mbbl/d, or some 33% of total global oil production (Sandrea and Sandrea 2007). This percentage is only approximate and will vary depending on 'what' is counted (only crude oil or all liquids).

Figure A.1 below shows offshore crude oil production over time. Shallow offshore production has been maintained stable over the last ten years. Deep offshore activity beginning from the late eighties has increased oil production to almost 5 mmbbl/d until 2007.




Source: (Sandrea and Sandrea, 2007)

**Figure A.1** Offshore oil production over time, from both shallow and deepwater operations.

In the United States, offshore crude oil production accounts for approximately 22 percent of total crude oil production.  Of this crude oil production, the majority is found within the Gulf of Mexico which is offshore production and therefore outside federal jurisdiction.  These statistics do not include natural gas liquids production or lease condensate.

For further information about oil production, onshore vs. offshore see table A.3.for links to EIA data sources.

**Table A.3.** Year 2006 U.S. crude oil production, onshore vs. offshore.

| **Quantity** | **Oil Prod. (Mbbl)** | **Website of datatable** |
|---|---|---|
| Onshore | 1862 | http://tonto.eia.doe.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_m.htm |
| State Offshore | 121 | http://tonto.eia.doe.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_m.htm |
| Gulf of Mexico Federal Offshore | 406 | http://tonto.eia.doe.gov/dnav/pet/pet_crd_gom_s1_a.htm |
| **Percentage offshore** | **0.22** | |

With regard to exploratory drilling, the current rate of success is about 35% (Sandrea and Sandrea 2007).  Related data are shown below in Figure A.2. which plots wells drilled (shallow and deep) and the number of fields discovered.

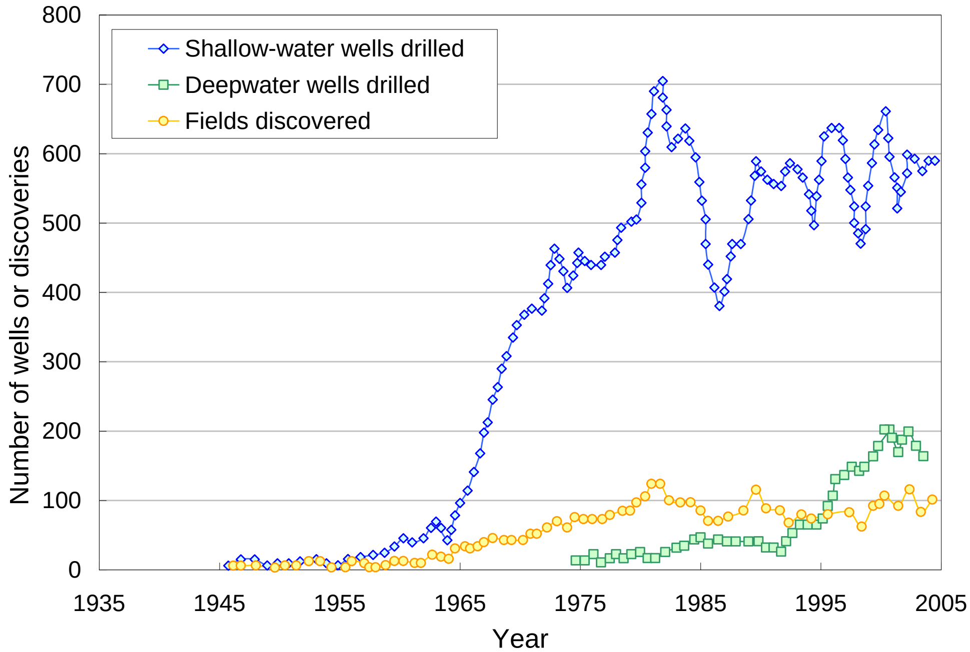
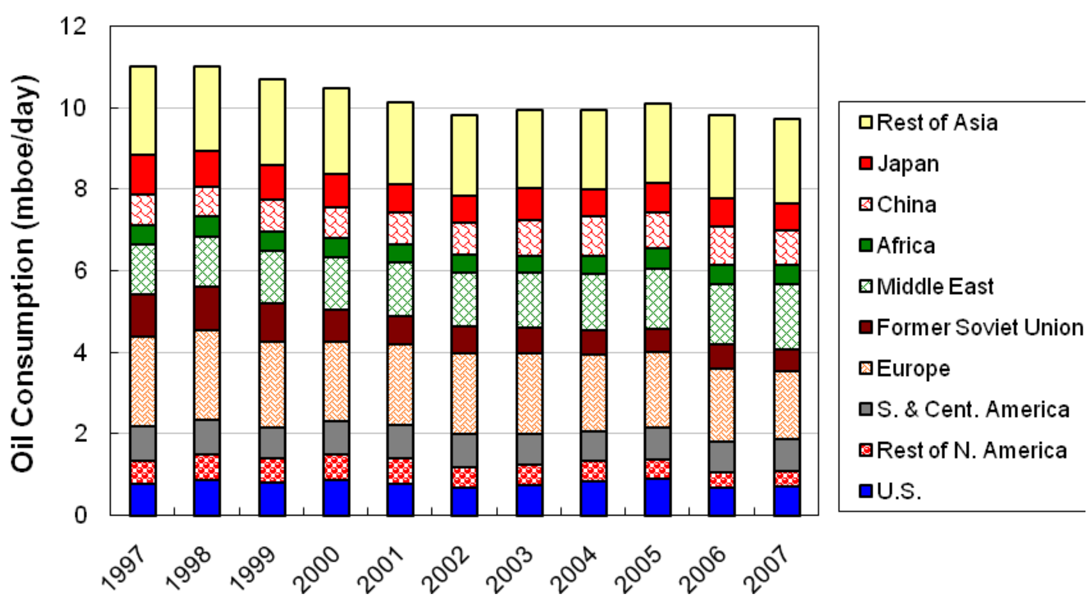



**Figure A.2.** Offshore exploratory drilling rates, shallow and deepwater.

The trends in these figures indicated growth in deep offshore production, which will be more energy intensive and costly than comparable shallow water projects.

## A.3.Trends in Petroleum Coke and Residual Oil Markets

Figure A.3. cites the worldwide trends of heavy oil consumption showing an overall decrease in heavy oil consumption from about 11 mboe/day in 1997 to less than 10 mboe/day in 2007.




Source: BP 2008

**Figure A.3.** Worldwide trends in heavy oil consumption

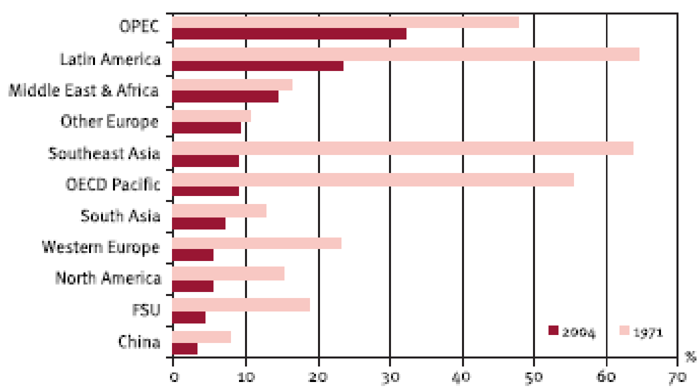
### *Regional consumption of fuel oil*

The most notable trend in demand by product is the continuing shift to middle distillates and light products. Demand for residual fuel oil, including marine bunkers and refinery fuel, is projected to remain stable, close to its current levels of around 10 mb/d. Residual fuel use in the industry sector and for electricity generation will decline globally.

### *Oil for Power Generation*

Despite the expected continued expansion in electricity production and consumption, the prospects for oil demand growth in this sector are limited. In fact, there have been some dramatic movements in this sector's oil usage over the past three decades.

For example, according to Figure A.4 in 1971 56% of the inputs to electricity generation in the OECD Pacific was accounted for by oil, while by 2004 this had fallen to just 9%. This movement was primarily in reaction to the oil price rises of the 1970s, which led to major efforts to develop alternatives to oil in the electricity sector. Other OECD countries have also reduced reliance on oil in this sector, with the region now accounting for an average of just 5% oil use in electricity generation. Developing countries are also generally using modest volumes of oil. The most dramatic example in this sector is Southeast Asia, where the share fell from 64% in 1971 to 9% in 2004. Many countries in Latin America, as well as OPEC Member Countries, however, still rely upon oil for a large portion of electricity. Figure A.4. shows that the oil share in electricity generation in 1971 compared to 2004 (OPEC).




Source: (OPEC 2007)

**Figure A.4.** Oil share in electricity generation: 1971 vs 2004 generated.

Coal continues to account for the largest share of electricity generated, although there are considerable differences between world regions, which is largely attributed to resource availability. For example, in 2004, coal accounted for as much as 50% of inputs to electricity generation in North America, 71% in South Asia, and as much as 89% in China, all regions with abundant coal reserves. Elsewhere, in regions such as Latin America and OPEC countries, the average is well below 10%. Continued additions of coal-based generation capacity, particularly in the U.S. and outside of the OECD, should mean that this fuel retains its strong position in this sector. Indeed, in recent years, the U.S. has seen coal use grow faster than natural gas.

However, the global share of natural gas has also risen steeply over the past two decades. For example, in Western Europe in the early 1990s, gas accounted for just 6% of the inputs to electricity generation, but this rose to 17% in 2004. Southeast Asia witnessed an even more rapid rate of penetration, increasing from below 10% in 1990 to around 38% by 2004. Gas has steadily consolidated its position as the fuel of choice in this sector in OPEC Member Countries, accounting for over 50% of the inputs to electricity generation for the past ten years. Throughout the world, gas-fired plants benefit from the efficiency of combined-cycle technology, as well helping meet environmental concerns over the effect of emissions at both local and global levels.

Some large developing countries are also considering developing nuclear power generation, for example China and India. Even though renewables will rise over the next few decades, they do from a low base, and thus their overall share is not likely to change dramatically. Hydropower will witness a modest expansion, primarily in Asia and Central America.

With these developments in mind, it is not expected that oil demand will experience growth to any significant degree in the electricity generation sector. As expected, no growth appears in the OECD region. Similarly, within developing countries, continued switching leads to low or no growth in China and Southeast Asia.

However, other developing country regions are expected to account for some growth, amounting to a little over 1 mboe/d in total over the projection period. Table A.4. shows also that North America well have a modest growth of oil consumption for electricity generation until 2030 of about 0.2 mboe/d.

**Table A.4.** HFO, LFO and Diesel demand in electricity generation.

| **Region** | **Demand Level (mboe/d)** | | | | **Growth** |
|---|---|---|---|---|---|
| | 2006 | 2010 | 2020 | 2030 | 2006–2030 |
| North America | 1.1 | 1.1 | 1.2 | 1.3 | 0.2 |
| Western Europe | 0.8 | 0.7 | 0.7 | 0.6 | –0.2 |
| OECD Pacific | 0.7 | 0.7 | 0.6 | 0.4 | –0.3 |
| OECD | 2.6 | 2.6 | 2.4 | 2.4 | –0.3 |
| Latin America | 0.3 | 0.3 | 0.3 | 0.3 | 0.0 |
| Middle East & Africa | 0.4 | 0.5 | 0.6 | 0.8 | 0.3 |
| South Asia | 0.3 | 0.3 | 0.4 | 0.5 | 0.2 |
| Southeast Asia | 0.2 | 0.2 | 0.2 | 0.2 | 0.0 |
| China | 0.3 | 0.3 | 0.2 | 0.2 | –0.1 |
| OPEC | 1.3 | 1.4 | 1.5 | 1.5 | 0.2 |
| Developing Countries | 2.8 | 2.9 | 3.2 | 3.5 | 0.7 |
| FSU | 0.3 | 0.3 | 0.2 | 0.2 | –0.2 |
| Other Europe | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 |
| Transition economies | 0.4 | 0.4 | 0.3 | 0.2 | –0.2 |
| World | 5.8 | 5.8 | 5.9 | 6.1 | 0.3 |

Source: OPEC 2008

### *Marine Bunker Fuel*

Expansion in global maritime trade will likely necessitate the growth in residual fuel as a bunker fuel. Demand in marine bunkers is expected to grow by more than 3 mboe/d over the period 2006–2030. This rise will be driven by increased trade, including that of oil, although the expansion will be kept moderate by ongoing efficiency improvements. Trends in marine bunker fuel are shown in Table A.5.

**Table A.5.** Oil demand in marine bunkers

| **Region** | **Demand Level in mboe/d** | | | | **Growth** |
|---|---|---|---|---|---|
| | **2006** | **2010** | **2020** | **2030** | **2006–2030** |
| North America | 0.6 | 0.6 | 0.6 | 0.6 | 0.0 |
| Western Europe | 1.0 | 1.1 | 1.5 | 1.8 | 0.8 |
| OECD Pacific | 0.3 | 0.3 | 0.3 | 0.2 | 0.0 |
| OECD | 1.8 | 1.9 | 2.3 | 2.6 | 0.8 |
| Latin America | 0.1 | 0.1 | 0.2 | 0.3 | 0.1 |
| Middle East & Africa | 0.1 | 0.1 | 0.1 | 0.2 | 0.0 |
| South Asia | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Southeast Asia | 0.7 | 0.7 | 1.1 | 1.7 | 1.0 |
| China | 0.2 | 0.3 | 0.7 | 1.6 | 1.4 |
| OPEC | 0.3 | 0.3 | 0.3 | 0.4 | 0.1 |
| DCs | 1.4 | 1.5 | 2.5 | 4.1 | 2.8 |
| FSU | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Other Europe | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 |
| Transition economies | 0.0 | 0.0 | 0.1 | 0.1 | 0.0 |
| World | 2.8 | 2.9 | 3.7 | 5.1 | 2.3 |

Source: OPEC 2008

Potentially offsetting such projections are the possible effects of any new marine fuels regulations. The International Maritime Organization (IMO) has only recently finalized new proposals and is in the process of having them ratified. However, unless on-board 'scrubbing' technologies prove to be commercially successful and environmentally acceptable, the regulations as finalized presage a total shift by 2020 or 2025 to marine fuels of either 0.1% or 0.5% sulfur, which could lead to a partial or possibly even total conversion from intermediate fuel oil (IFO) to distillate grades. The uncertainties lie in the rate of adoption of the new IMO regulations, the timing of the implementation of regional 'Emissions Control Areas' (ECAs) at the 0.1% sulfur standard and of the global 0.5% standard – plus the degree to which scrubbers are used. Needless to say, such regulations would significantly alter projections for residual fuel demand.

Moreover, increasing bunker costs and a surplus of capacity normally have boosted the practice of slow steaming in order to reduce fuel consumption. For example, most lines on the Asia-Europe trade have cut their speed from 24 knots to 21 knots and are deploying nine instead of eight vessels to maintain the schedule. Reducing speed is the quickest way for the shipping industry to cut fuel consumption. Some owners have already begun to order new vessels with smaller engines.

### *Petroleum Coke*

There are several potential markets for pet coke. Petroleum coke is used in steel making and also exported for power plant fuel. Note that the additional emissions associated with the export of petroleum coke from U.S. refineries to Asia are not considered in life cycle analyses.

The emissions for the base case gasoline production are also segmented by crude oil source regions (CA, AK, and imports). The imported gasoline or crude oil can be considered the marginal production resource. Emissions associated with residual oil and coke combustion are about 10% of the total emissions when these co-products are represented in proportion to gasoline fuel production. The appropriate allocation of these emissions would address how these would change with a change in gasoline production.

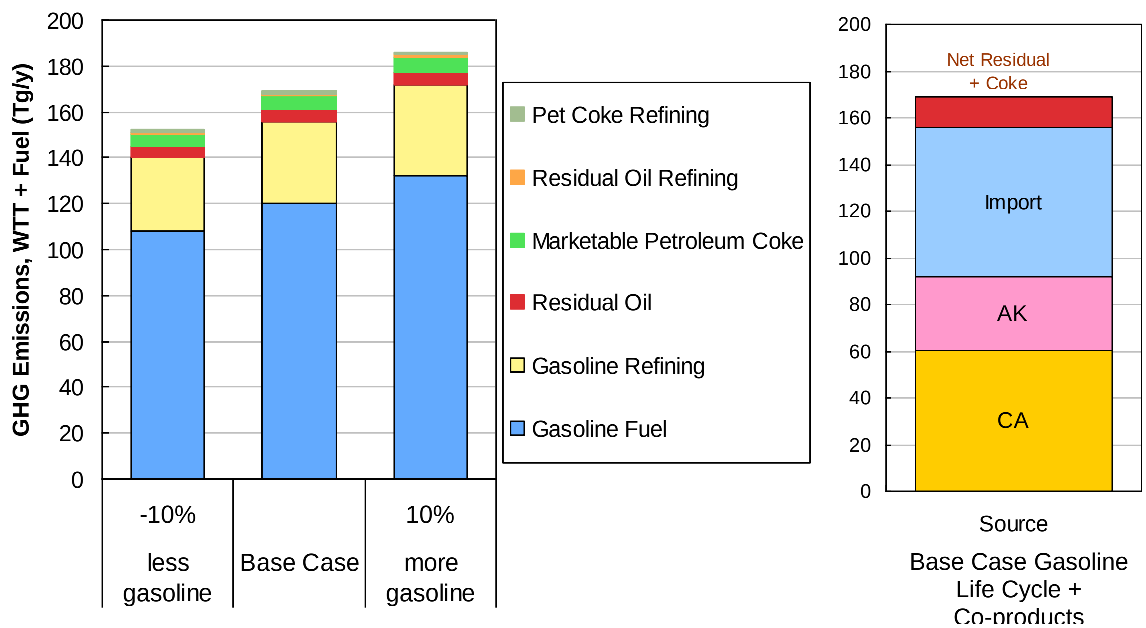



**Figure A.5.** Scenario for total GHG emissions associated with CA gasoline production.

Figure A.5. shows the energy inputs and GHG emissions associated with each of the fuel categories. The combustion of co-products corresponds to 8 g $CO_2$e/MJ of gasoline. All of these emission reductions would not occur with a reduction in refinery output. The following table A.6. shows the results of the calculations and the range in these indirect emissions.

**Table A.6.** Energy Flows and Emissions Associated with Refinery Co-Products.

| CA scenario | less gasoline | Base Case | more gasoline |
|---|---|---|---|
| | -10% | | 10% |
| Total Fuel Demand (bgal/y) | 12.6 | 14 | 15.4 |
| | | | |
| Energy (PJ/y) | | | |
| Gasoline | 1499 | 1666 | 1833 |
| Gasoline WTT (PJ/y) | | | |
| Gasoline Refining | 457.3 | 508.1 | 558.9 |
| Residual Oil | 68.9 | 76.6 | 84.3 |
| Marketable Petroleum Coke | 65.2 | 72.5 | 79.7 |
| Residual Oil Refining | 0.43 | 0.48 | 0.52 |
| Pet Coke Refining | 0.48 | 0.53 | 0.59 |
| | | | |
| Delta Gasoline (PJ/y) | -167 | 0 | 167 |
| GHG Emissions (Tg/y) | | | |
| Gasoline Fuel | 108 | 120 | 132 |
| Gasoline WTT | | | |
| Gasoline Refining | 32.39 | 35.986 | 39.58 |
| Co-products | | | |
| Residual Oil | 4.45 | 4.942 | 5.44 |
| Marketable Petroleum Coke | 5.74 | 6.378 | 7.02 |
| Residual Oil Refining | 0.77 | 0.860 | 0.95 |
| Pet Coke Refining | 0.92 | 1.018 | 1.12 |
| | | | |
| Total Co-product | 11.9 | 13.2 | 14.5 |
| Delta Co-product | -1.320 | 0.000 | 1.320 |
| Delta Co-product (g/MJ) | 7.92 | -- | 7.92 |

## A.4. Indirect Refinery Co-Product Emissions

The emissions associated with the use of residual oil are shown in Table A.7. These values do not take into account market shifts in fuel usage. Residual oil comprises 4.6% of U.S. refinery output. With a fixed refinery configuration, the amount of residual oil available on the market would drop by this fraction. However, on the margin, imports from more remote locations would be reduced if refinery output drops (or growth is limited). The average distance for imported fuels to California is 7800 miles, which corresponds to about 1.1% of the energy input to gasoline production. Thus, reducing gasoline output would reduce the amount of residual oil that is produced, but less residual oil would be used for crude oil transport.

Also shown are the emissions associated with electric power generation from fuel oil. 0.01 MJ of electric power could be produced from the net residual oil available from oil refining. The emissions associated with the same amount of electric power from natural gas, coal, and renewables is also shown as well as the net change in emissions. As indicated, switching from residual oil to natural gas fired power would result in a GHG emission reduction of 1 g $CO_2e$/MJ of gasoline, while emissions would increase if coal were to displace residual oil fired power. Of course, conservation or renewable power would reduce emissions further. These emission estimates only bound the effect of residual oil production associated with gasoline production as market forces could result in further fuel switching, conservation, and a mix of these results.

**Table A.7.** Direct Emissions Associated with Residual Oil Usage and Electric Power Production.

| WTT Attribution | Energy Output and GHG Emission Savings | |
|---|---|---|
| Residual Oil Production | 0.046 | J/J gasoline |
| Bunker Fuel for Crude Transport | 0.011 | J/J gasoline |
| Bunker Fuel | | |
| Less ship trade | 3.3 | g/MJ |
| Displaced Electric Power | | |
| Residual Oil Power Fuel | 0.035 | MJ Fuel Energy/MJ gasoline |
| Power Production Efficiency | 0.32 | MJe/MJ Residual Oil |
| Residual Oil Power | 0.01 | MJe/MJ Gasoline |
| Power Generation Emissions | | |
| Residual Oil Power | 2.84 | g $CO_2e$/MJ Gasoline |
| NG Fired Power | 1.69 | g $CO_2e$/MJ Gasoline |
| Coal Fired Power | 3.70 | g $CO_2e$/MJ Gasoline |
| Renewable Power | 0 | g $CO_2e$/MJ Gasoline |
| Net Difference | | |
| Residual Oil Power | -- | |
| NG Fired Power | 1.15 | g $CO_2e$/MJ Gasoline |
| Coal Fired Power | -0.86 | g $CO_2e$/MJ Gasoline |
| Renewable Power | 2.84 | g $CO_2e$/MJ Gasoline |

Table A.6. shows a scoping calculation for the market mitigated effect of refinery co-products. The GHG emissions associated with bunker fuel usage are multiplied by an assumed market share and elasticity factor. The market share assumptions reflect the mix of fuel oil uses that would be displaced and are provided for illustration purposes. The elasticity factor reflects that fuel demand would respond to a reduction in supply. A 20% elasticity factor means that fuel use is reduced by 20% and the remaining 80% of users find a substitute. In the case of bunker fuel, crude oil could be a substitute. In the case of new sources of electric power displacing crude oil, a 0% elasticity factor assumes that total power consumption remains constant. A similar calculation is provided for petroleum coke. Here a 20% elasticity factor refers to a reduction in total uses of petroleum coke. The remaining 80% would use substitutes such as coal with comparable GHG emissions.

Again the calculations in Table A.8. are provided as a scoping calculation to show the potential range in GHG emissions associated with high carbon refinery co-products.

**Table A.8.** Example of Market Mitigated Emissions Associated with Refinery Co-Products

| Market Mitigated Estimate | Residual Oil Market Share | Assumed Elasticity | Change in GHG Emissions (g $CO_2$e/MJ Gasoline) |
|---|---|---|---|
| Shipping | 40% | 20% | 0.27 |
| Displace NG Power | 20% | 0% | 0.23 |
| Displace Coal Power | 20% | 0% | -0.17 |
| Displace Renewable Power | 20% | 0% | 0.57 |
| Total Effect of Residual Oil Production | | | 0.89 |
| Marketable Pet Coke | | 20% | 1.04 |
| Other Petroleum Products | | 20% | 0.10 |
| Total Market Mitigated Estimate | | | **2.0** |