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From Ground to Gate: A lifecycle assessment of petroleum processing activities in the United Kingdom

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Abstract

Petroleum products are an important component of today's societal energy needs. Petroleum powers everything from the vehicles people rely on, to the ships that carry goods around the world, to the heating of homes in colder climates. The petroleum process chain is complex and the environmental impacts within the process chain are not always well understood. A deeper understanding of where emissions come from along the process chain will help policy makers in the path towards a less carbon intensive society.

One of the core processes of the petroleum process chain is refining. Petroleum refining is a complicated process which can have varying crude inputs and varying fuel outputs depending upon the refinery make-up, the crude blend and the market conditions at the time of production.

The goal of this paper is to introduce a lifecycle analysis on the UK petroleum refining sector. Where emissions occur along the process chain and which fuels cause the most pollution on a per unit basis will be reported and discussed using lifecycle analysis framework. The refining process is difficult to maneuver around and it can be difficult to discern which processes create which products. The analysis is broadened to understand the refining emissions associated with different fuel types at both a process and country level. The results can be relevant for environmental policy and decision makers.

The original intent of this paper was to include gas processing. After discussion between advisor and student, the gas processing was not included after mutual agreement.

Acknowledgements

This study could not have been organized without the guidance of Anders Hammer-Strømman who was the main advisor for all work. Nick Vandervell and Andy Roberts of UKPIA were the sources of much information. The work of DECC provided the basis for comparison while the NAEI had the necessary refinery information to perform analysis. Anthony Pak must be thanked for his previous work on UK petroleum extraction which was used in this study. Additional thanks to Vladimir Volsky, who helped shape the dialogue of the paper and provided personal guidance when asked.

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UK	United Kingdom	FDP	Fossil depletion
DECC	UK Department of Energy and Climate Change	FETPinf	Freshwater ecotoxicity
UKPIA	UK Petroleum Industry Association	FEP	Freshwater eutrophication
NAEI	UK National Air Emissions Inventory	HTPinf	Human toxicity
OPEC	Organization of Petroleum Exporting Countries	IRP_HE	Ionising radiation
LCA	Lifecycle analysis	METPinf	Marine ecotoxicity
LCI	Lifecycle inventory	MEP	Marine eutrophication
CO2-eq	Carbon dioxide equivalent	MDP	Metal depletion
DERV	Diesel engine road vehicle (fuel)	NLTP	Natural land transformation
LDF	Low density fuel	ODPinf	Ozone depletion
MDF	Medium density fuel	PMFP	Particulate matter formation
LPG	Liquid petroleum gases	POFP	photochemical oxidant formation
CHP	Combined heat and power	TAP100	terrestrial acidification
GHG	Greenhouse gas	TETPinf	terrestrial ecotoxicity
EFQ	European Fuel Quality Directive	ULOP	urban land occupation
ALOP	Agricultural land occupation	WDP	water depletion
GWP	Global warming potential		

Introduction

Currently the world is facing a crisis between the limits of nature and the ambitions of mankind. Anthropogenic pollution is slowly altering the earth's natural systems where the outcomes and impacts can have grave effects. Most notably, climate change from the release of carbon dioxide and other pollutants can create complex problems for society as it is known today. Social upheavals, widespread agricultural duress, and the large scale destruction of human and economic infrastructure are all possible outcomes of an altered climate. It is up to humans to first understand how and where this pollution is occurring and then to use this knowledge to create sustainable economic and social systems.

One of the major drivers of climate change is the use of fossil fuels. Direct combustion of fossil fuels is the most well understood part of the petroleum fuel process chain but what is less understood is the emissions associated with other links in the chain. The combustion of fossil fuels is not the complete picture. Extraction, refining, distribution and other processes make up the petroleum process chain and each process contributes to the indirect emissions of fuel usage. Ignoring the rest of the picture is like eating an apple but not acknowledging it came from a tree. Understanding this picture requires analysis and understanding the emissions along the process chain requires lifecycle analysis. This paper focuses its lens on the United Kingdom (UK) and the petroleum processing industry there.

The European Union strives to reduce GHG emissions and reduce human health impacts through a program known as the European Fuel Quality Directive (EFQ). The EFQ places a burden on parts of the petroleum process chain but specifically targets petroleum suppliers to reduce lifecycle GHG emissions by minimum of 6% by 2020 from 2010 levels (European Union, 2009). How this is done depends on the refinery producers. The first step is determining where in the process chain emissions can be reduced and how the UK petroleum producers can meet the emissions reduction targets of the EFQ while providing fuels. The EFQ is an important impetus for producers to reduce their impacts as the production of petroleum can constitute nearly 10% of the lifecycle GHG emissions of a car and upwards of 90% of the non-methane volatile organic compounds (DaimlerChrysler AG, 2006) . The petroleum processing industry in the UK and around the world must focus their efforts to reduce emissions.

Overview of Petroleum Activities in the UK

Petroleum was first discovered in the North Sea region of Europe more than 40 years ago and has transformed the region to a highly developed energy economy where petroleum extraction and processing forms one of the major cogs. As part owner of the North Sea petroleum reserves, the UK has found itself a major player in the petroleum industry worldwide.

Domestic extraction, world class refining plants, and large quantities of domestic consumption have allowed for the UK economy to flourish since petroleum extraction began in the 1960s. The UK petroleum sector has been well organized to allow for the vertical integration of the process chain with more than 100 offshore extraction units, 40,000 km of pipeline, 8 major refineries and more than 5500 distribution points for petroleum products. The UK economy is heavily reliant on the petroleum process chain attributing more than 200,000 jobs directly from the process chain with another 100,000+ as spin-off jobs (Oil and Gas UK, 2011). The petroleum refining industry constitutes a major part of the UK petroleum sector both in terms of economic activity and emissions.

The UK petroleum industry follows a process chain that involves extraction, processing (refining), distribution and delivery to the end user for combustion. Although this is a grossly simplified process chain, it is a common process chain among all petroleum producers worldwide. A summary of this simplified process chain is found below.

Figure 1 - The simplified petroleum process chain

When petroleum is extracted from the ground, it emerges as a crude mixture of differently sequenced carbon bonds that have to be separated. To separate this crude mixture into something palatable for combustion, it must go through a petroleum refinery. Operating a petroleum refinery requires energy, infrastructure, land and other inputs to create the various outputs required by industry and consumer alike. The petroleum refining process is also quite often complex, meaning that inputs do not always have a clear path to specific outputs. Outputs are co-products which means that assigning environmental impacts to different refining processes or different outputs becomes tricky. Nonetheless, refining is a critical part of the chain, without which, almost no crude can be used for meaningful combustion.

The UK processes more than 70,000 kilotons of crude petroleum every year with most of it extracted from North Sea platforms located in British and Norwegian waters (UK Department of Energy and Climate Change, 2009). In recent years the refining industry has faced declines due to reduced output from North Sea fields and from reduced consumption in the domestic economy. All told, this has also reduced CO2 output to the atmosphere due to refining. This reduction comes with a caveat, however, as the CO2 emissions per unit have been steadily increasing. The UK refining industry has become less environmentally efficient on a per unit basis (UK Department of Energy and Climate Change, 2012).

The chart below summarizes these trends. On the left axis is total crude throughput in kiltons broken down between crude that is used as energy in the refining process (feedstocks) and crude that becomes output to the market (net output). The right axis has kilotons of CO2 per kiloton refined fuel.

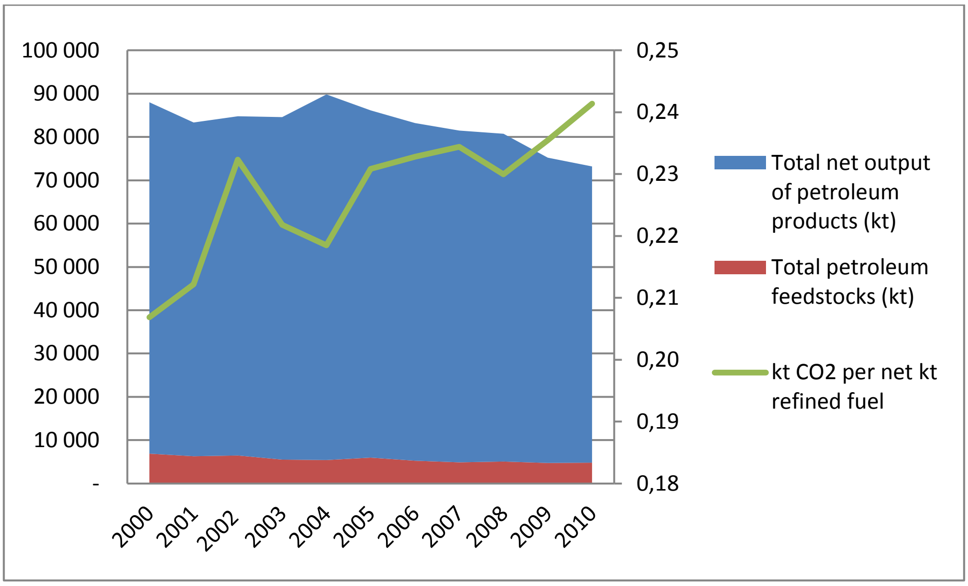

Figure 2 - UK total production and CO2 emissions per kt

As shown on the chart, UK refinery output has been trending a steady decline from a ten year peak in 2004 to current levels today. This trend is set to continue. Curiously, the direct CO2 emissions from the refining process are increasing on a per unit basis. The direct emissions from refining are somewhat understood but the data is missing the other indirect emissions.

State of the field

The UK Department of Energy and Climate Change (DECC) is responsible for reporting on all things related to energy in the UK. As part of their mandate, the DECC releases a comprehensive report on all aspects of energy production every year (UK Department of Energy and Climate Change, 2009). This report is accompanied with data relating to the report and its findings. There is always a chapter dedicated to the petroleum industry which outlines the entire process chain on a macro-level. The report describes the quantitative information in a broad sense, describing all manners of production data, consumption patterns, extraction production figures and more. The report does not delve in to depth on individual or plant-level figures but instead is a glimpse of the industry as a whole.

Additionally, data which is available in bulk form is often not of the highest resolution to garner meaningful information from.

On the converse, the UK National Atmospheric Emissions Inventory (NAEI) offers more localized data that can offer more resolution on the point source air emissions released by industrial operations in the UK. The NAEI is a government program which records air emissions information from industry and compiles this information on a registry (AEA, 2009) . The organization is a joint effort between all UK governments and covers emissions for the entire UK. The NAEI has only recently begun with the efforts of recording these emissions, which are usually industry reported or sometimes estimated by the organization. The NAEI has comprehensive, point source information for most industrial operations but only for the year 2009. This data is available in bulk download and contains a wealth of information but it does not offer very much in the way of process separation. Each industry source is broken down into one or two categories which are reported. Generally, these categories are "emissions from combustion" or "other emissions", which again do not offer a deeper understanding of how or where the emissions are greatest.

The EcoInvent database has a large mix of inventory data pertaining to petroleum products and their environmental emissions. EcoInvent has two sets of figures for six major fuel types: petrol, diesel, heavy fuel oil, light fuel oil, naphtha and butane/propane. The fuel oils, diesel and petrol inventories also have additional information on which processes they follow after primary separation depending on the sulfur content, which may or may not need to be removed. The main EcoInvent data comes from European averages and is reflective of Europe in general but not the UK specifically. The EcoInvent data makes some fairly robust assumptions which are not necessarily indicative of specific refineries or production in specific countries. The EcoInvent inventories also contain information on Swiss refineries, but this data is only specific to that country. That means that the EcoInvent inventories do not have specific information relating to UK petroleum refining operations. Furthermore, much of the data for refining comes from the year 2003 or earlier, which is outdated for today's refining industry (Frischknecht, 2007). Given the trends in the UK industry, refining production today has changed greatly from years prior.

The state of the field is such that UK refining emissions are known in certain capacities but unknown in others. An outline of the known inventory data is shown in figure 3.

Data source	Data type	Latest Year	Data scope
DECC	Overall UK emissions related to refining	2011	Only CO2 emissions, not process specific
NAIE	Overall emissions by refinery	2009	Only emissions to air, not process specific
EcoInvent	Average European emissions per unit fuel refined	2003	Comprehensive but not UK specific
Study	*Average UK emissions per unit fuel refined*	*2009*	*Comprehensive and UK specific*

Figure 3 - Overview of main emissions data sources

There are several studies that utilize EcoInvent data for determining the impacts of refineries. Besides using EcoInvent data and setting up a system based on emission outputs, one can also analyze the energy inputs to production to approximate direct emissions.

In the Venkatesh et al study "Uncertainty Analysis of Life Cycle Greenhouse Gas Emissions from Petroleum-Based Fuels and Impacts on Low Carbon Fuel Policies", the main method for determining emissions output comes from energy use and fixed energy emission values (Venkatesh, Jaramillo, Michael, & Matthews, 2011). The study emphasizes energy use above all else and uses a system boundary that is from well to wheel such that there is no breakdown between processes. Additionally, the study comes from the United States and uses time series data that is from 1998 to 2008 respectively.

Another study that follows the same energy input rubric is the study by Wang et al called "Allocation of Energy Use in Petroleum Refineries to Petroleum Products" that analyzes energy usage from well to pump (Wang, Lee, & Molburg, 2003). The Wang study implements the same model as the Venkatesh study except that it separates the emissions more cleanly by process and uses older data from 1996 and 1999 within the geographical boundaries of the US. For this study and others like it, the GREET model for energy usage was used. The Venkatesh study also uses the GREET model.

Both the Venkatesh and Wang studies are good bases to work from but they neglect the entire emissions picture. These studies are only interested in the CO2 emissions and are based solely on energy inputs. They offer a small glimpse of how different fuel types produce different emissions but are not inclusive of all processes within a refinery.

As far as product lifecycles are concerned, Mercedes Corporation analyzes the full lifecycle emissions of their vehicles through lifecycle analysis studies (DaimlerChrysler AG, 2006). These studies are relevant because they encompass the energy production within the lifecycle impact assessments and work with a wider scope. These studies do not go into detail on petroleum processing but are at least useful when trying to decipher the petroleum processing impacts in the lifecycle use of products. What Mercedes has accomplished is a presentation of relevant lifecycle emissions for their vehicles which includes emissions from petroleum processing but not at a level of resolution that can be used by petroleum producers.

Motivation

In order for refining firms to fulfill their obligations to the European Fuel Quality Directive, refinery emissions must be isolated on a level that can help refiners pinpoint and reduce their impacts. The fuels which offer the greatest environmental efficiency must be promoted for production and the technology that reduces emissions the most must be implemented. Higher resolution on emissions must be the first step in determining where to reduce impacts.

The main purpose of this study is to determine the environmental impacts of the petroleum industry from the point of extraction to the gates of the refinery. The results should be compared to what exists in the field presently and used to provide a base from which the UK petroleum industry can be compared to other refining nations. Additionally, technology implementation should be analyzed so that the best information can be made available based on the results of the study.

The current data that is available and the information that is known provide a weak basis for determining how environmental policy makers ought to work with UK refiners. In order to understand which fuels are less environmentally intensive, a full picture of the process chain needs to be made. Refining emissions inventories in their current form do not assign emissions based on fuel type outside of the combustion phase. This is not a fault of the organizations dedicated to environmental protection and monitoring in the UK but rather something that has not been deeply examined. Therefore the purpose of this study is to try and determine how UK refinery emissions can be broken down and how the processes leading into refining affect the overall emissions reported.

There exists information on refining on a national level and information on a plant level but the resolution is not much greater than that, or if it is available, it comes from non-UK specific sources that do not focus on the UK. Barring the difficulties of determining specific process emissions, this project is designed to decipher the emissions on an output basis. That is to say, which petroleum products, create the greatest emissions when produced.

There is a lack of resolution from the data that is currently available. An environmental policy decision maker can discuss which fuels are the most emissions intensive at the point of combustion and have a general sense of the emissions further up the process chain but without greater resolution, these decisions come from only partial information. The need for this information comes from a desire to have greater congruity with the environmental reality. Without the relevant information, misinformed decisions can be made.

The results from this study are meant to give greater depth of understanding to environmental policy decision makers and researchers alike. The focus will be placed on the UK petroleum refining sector so as to contribute a link to the complete petroleum process chain in a major petroleum producing and consuming country.

The gaps that it begins to fill include increased resolution on fuel types, increased resolution on cradle to refinery gate emissions, and increased resolution on technology choices for UK refining. All of this analysis is an attempt to improve upon the information that relates to UK refining and petroleum processing. With greater information available, more insightful decisions can be made regarding fossil fuel usage in the UK.

Case description

The petroleum processing chain follows the typical trajectory of a production chain. The first phase is extraction from the geosphere, followed by processing, distribution, retailing then finally the use phase with transportation between each point. While it is quite simple to break down the stages of petroleum processing chain, it can be more difficult to break down the sub-processes that occur at each stage. In the processing portion of the chain (refining), more often than not it is nearly impossible to assign shares of resource usage and emissions for different fuel types. This is because the entire operation can be thought of a single series of co-products. To help understand why this is, it first important to understand how petroleum refining works.

The refining process and theory

Petroleum refining first began in earnest as a value added process in 1856 near the site where the Killingholm/Humber refinery sits today**.** Today's refineries are decidedly more sophisticated than in 1856 and rely on a fixed configuration that produces fixed output depending on the quality of the crude inputs and the capacity of the refinery. There are several processes involved in processing crude inputs to make them useable and marketable fuel outputs.

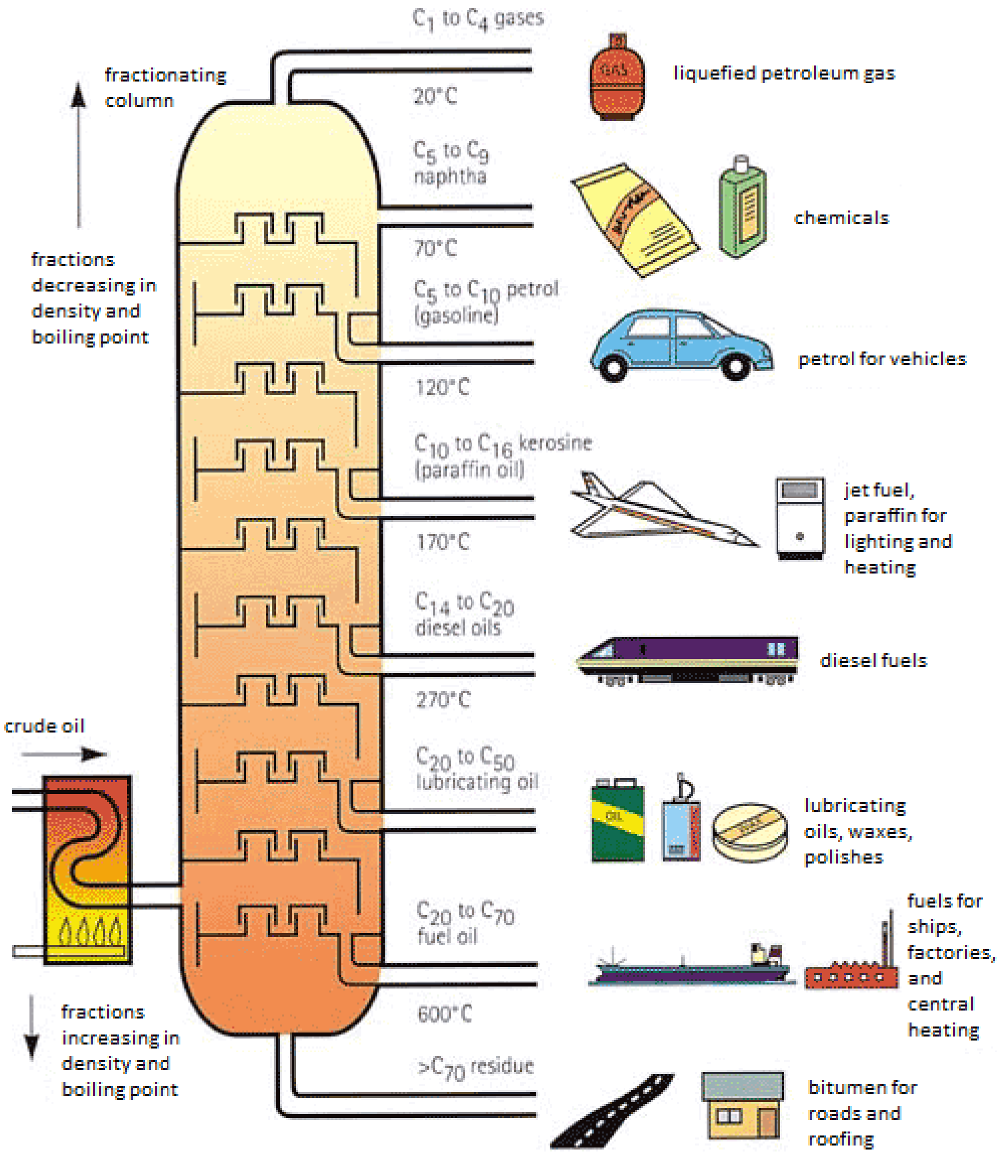

Figure 4 - Petroleum distillation column (Energy Institute)

The main refining processes can be described in terms of the order in which they occur. The most common form of petroleum refining is known as fractional or atmospheric distillation, which involves pumping the crude petroleum into the bottom of a heated column and then separating the fuels via different temperature levels (Energy Institute). The UK has a distillation capacity of 86 million tons of crude petroleum annually (UK Department of Energy and Climate Change, 2009). The distillation process is the primary process for all refineries in the UK and is summarized visually in the figure below.

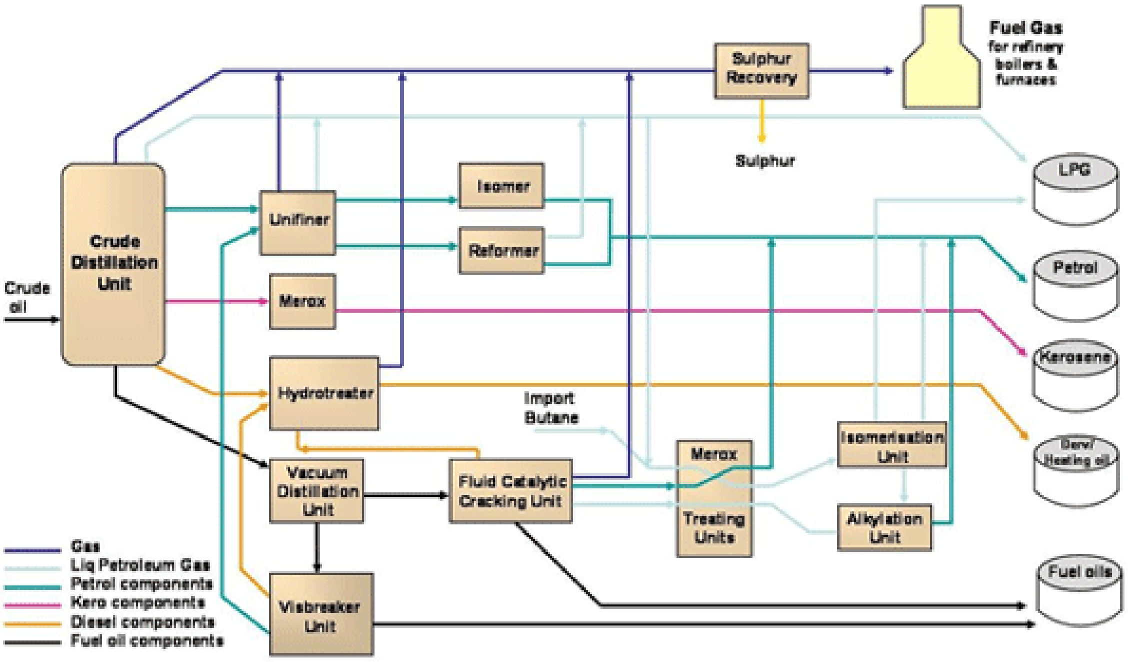

Figure 5 - Typical Petroleum Refinery Configuration

(UKPIA, 2012)

All fuels go through the initial distillation process to separate from crude oil on the way to further processing. The residue of the distillation column, much heavier than crude oil is then sent to a second distillation unit while the other fuel products are sent to other processes. The lightest products, liquefied petroleum gases, mostly butane, propane and naphtha require little to no further processing in order to be sold to market. However, other products require more processing in order to become marketable.

The main fuel products can be classified in the same way as the distillation column for simplicity's sake. The lighter products within the column rise while the heavier products sink. The additional processing that occurs can be summarized by fuel type and carbon structure.

Liquid petroleum gases (LPG) are most commonly in the form of naphtha, butane and propane. LPGs typically require little to no further processing except for sulfur removal. Sulfur removal (desulfurization) is also entirely dependent on the source of the crude and how much sulfur it contains.

Petrol is generally removed from the distillation unit and cleaned in what is called a unifiner. A unifiner removes sulfur and nitrogen compounds in the fuel and creates hydrogen sulfide and ammonia as wastes. Then the molecular structure is modified to increase the octane levels of the fuel so that it is suitable for combustion in motor vehicles and other petrol burning engines. Sulfur is a by-product of this process and is recycled in other processes or sent to waste processing. Petrol can also be separated from the heavy distillate residues through a process called catalytic cracking. Generally the more complex plants have catalytic crackers and are capable of refining heavier fuels. Catalytic cracking is an additional process and while adding value, also adds cost and emissions. The last step in petrol processing is fuel blending as required by national fuel specifications guided by the European Fuel Quality Directive.

Jet fuel and kerosene are generally grouped together because they have a similar carbon structure. They emerge from the distillation process requiring desulfurization. This is done through what is known as a merox unit, which washes the fuel with sodium hydroxide (caustic washing) and other additives which also help to reduce the impurities in the fuel.

Diesel and gas oil are used for combustion engines and heating purposes mostly. They require post-distillation processing in a unit known as a hydrotreater. The hydrotreater removes sulphur and other impurities using hydrogen recycled from other processes as a catalyst. The diesel and gas oil is typically ready for market after this process.

Fuel oils are generally used for heating and ship transport. These fuels require additional distillation through a process known as vacuum distillation. Vacuum distillation is a similar process to the primary distillation process except that the pressure within the distillation column is greatly reduced so that additional lighter fuels can be separated and captured for further processing. The lighter fuels that come out of the vacuum distillation unit are sent to a catalytic cracking unit and separated by fuel type to go through the remaining refining processes. The heavier fuels, or residues, from the vacuum distillation process are sent to a visbreaker. A visbreaker involves heating the heavy fuels to a very high temperature until they become less viscous. The products from the visbreaker are mixed with other products to make fuel oil blends that meet national fuel specification. *Lubricants* are also made through the process but not blended with other fuels.

The production process for each fuel chain is known with certainty but the problem is that there are many different outputs depending on the configuration of a refinery or the blend of crude oil which is inputted. Each refinery has a fixed proportion of output and will produce fuels based on the fixed configuration and infrastructure in place. It can be difficult to discern exactly which product is produced directly from a certain process because of how many processes are shared between products. A discussion on the problem of separating processes is discussed in the methods section.

The UK petroleum economy

The purpose of this paper is to analyze petroleum refining in the UK and its impacts on the environment. However, it is important to give context to the UK situation based on broad consumption and production patterns as well as emission patterns. Many factors contribute to the consumption patterns of UK citizens including price, government legislation, infrastructure, technology among others. Production can be just as affected by those factors but also by others such as labour strife, dwindling petroleum reserves, worldwide market price, profitability, seasonal demand and much more. While the discussion on production and consumption volatility is not a component of this paper, the patterns of petroleum production and consumption are well known in the UK and relevant to environmental policy decision makers.

Refining is a vital part of the overall petroleum industry in the UK and to understand the role that refining plays means understanding the market demands and the limitations of the crude petroleum reserves that operate within UK boundaries. However important the contribution of petroleum production to UK society may be, one simple truth exists in that petroleum production is on the decline, having peaked in the mid-1990s.

The following figure examines this in more detail. The left axis is the measurement of petroleum by fuel type in kilotons while the right axis is the measurement of total net petroleum production in kiltons for the UK. These figures are the final net production (gross production minus feedstock and process loss) and only account for fuels, excluding non-fuel petroleum products such as bitumen.

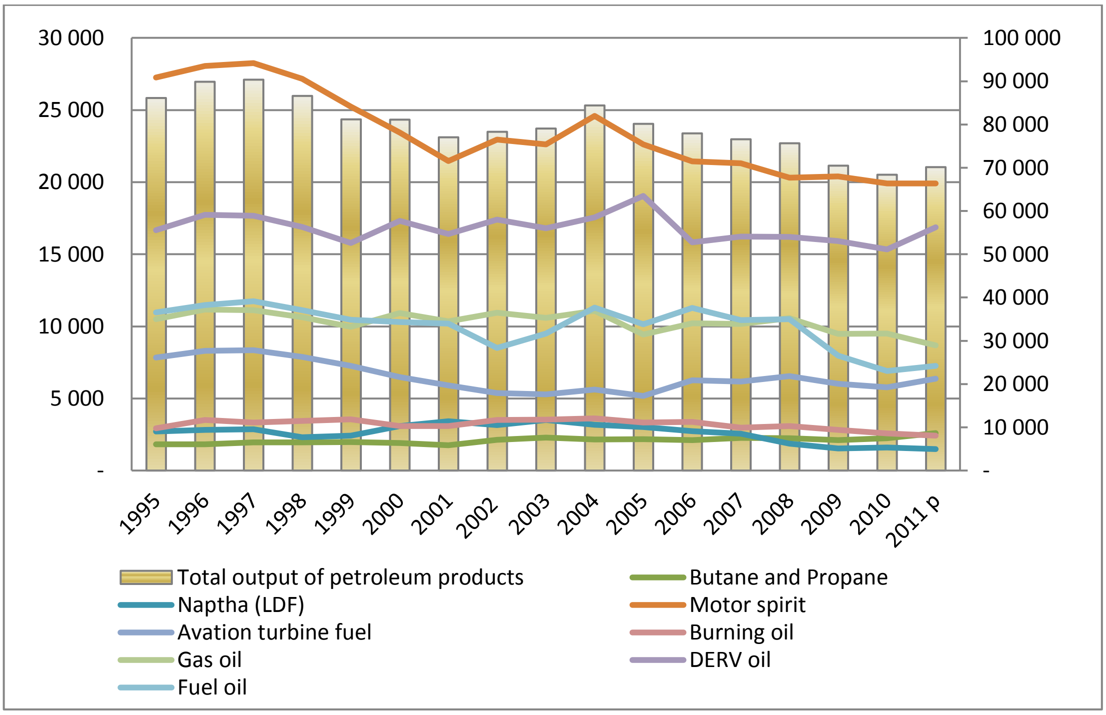

Figure 6 - Petroleum production by fuel type and total (in kilotons) in the UK, 1995-2011

The overarching trend shows the decline of net petroleum product output from a peak of 90,366 kilotons in 1997 to an estimated 70,154 kilotons in 2011 (UK Department of Energy and Climate Change, 2012). This is a decline of 22.4% from the peak total. Most of this decline can be seen in the parallel decline of petrol, as the domestic consumption patterns switch towards using diesel. Most other petroleum products are facing decline with the exception of single year upswings for DERV oil (diesel), fuel oil, and aviation turbine fuel. The general production trend for all fuels is either a long term flattening or decline in production.

The petroleum consumption patterns indicate a shift towards diesel fuel over petrol is due to the changing consumption patterns. Petroleum refiners are acutely aware of the changes in marketplace and rely on thin profit margins and volume sales to remain profitable. Processing the petroleum to meet the domestic and world market needs can be a challenge for UK refiners and a challenge for LCA practitioners to identify where emissions are occurring in the face of a dynamic economic environment.

The UK primary demand for all petroleum products has been on the decline since the year 2005. This is in tandem with the declining production figures and representative of a more energy efficient society. Most of the imports are comprised of diesel which is not able to be produced domestically in quantity to meet domestic demand. Most of the exports are petrol, which is in far greater demand abroad. The UK has remained a net exporter of petroleum products as a sum of all production but have been importing diesel as the North Sea crude that comprises most of the refinery throughput does not contain enough suitable carbon structures for diesel to meet domestic demand nor does the current refinery configuration allow for more diesel to be produced.

The following charts outline the patterns of production and consumption. The first chart is a summarized picture of petroleum production, primary demand, imports and exports all in kilotons of net refined output over the years 1999 to 2011. The second chart is a comparison between diesel and petrol demand and production in the UK and is also measured in kilotons over the years 2005 to 2011. (UK Department of Energy and Climate Change, 2012)

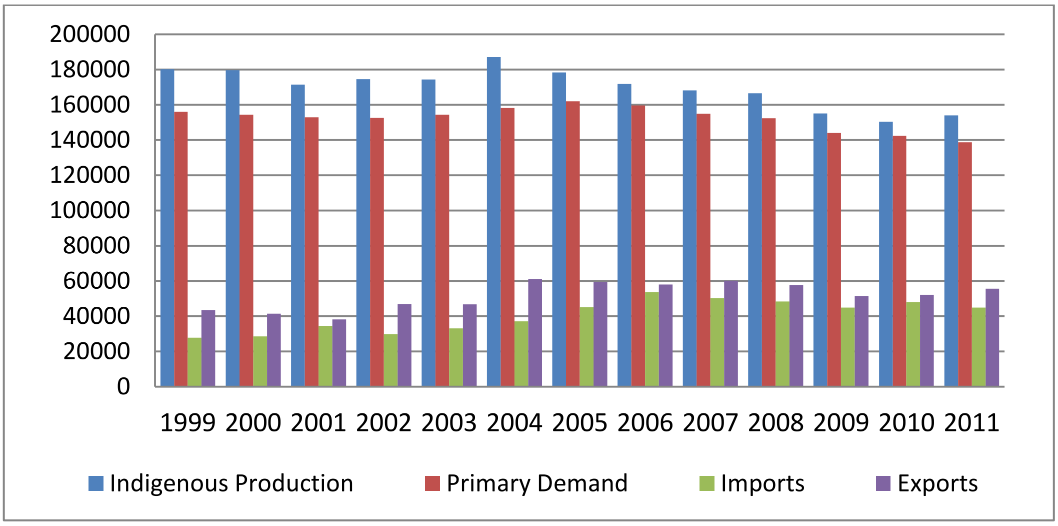

Figure 7 - Petroleum production and consumption patterns, UK, 2005-2011

The first chart shows the decline in production and the decline in consumption. The imports are increasing year over year primarily due to domestic diesel fuel demand while exports outstrip imports every year meaning that the UK is a net exporter. Whether this will continue in the future remains to be seen as petroleum reserves decline. It is important to note that this is a gross estimation of all petroleum products combined and does not differentiate between fuels of differing economic value or usage. To differentiate, a comparative chart of consumption and demand broken down between petrol and diesel is shown on figure 8.

The consumption trend for petrol (motor spirit) shows a steady decline in demand as denoted by the purple bars while diesel fuel has seen an increase over time as denoted by the green bars. Meanwhile, production of motor spirit has declined slowly while production of diesel shows a flat trend. This indicates that capacity for diesel has largely been reached. This conclusion can be reached because the demand for diesel outstrips domestic production. Anytime the red line is above the purple bars is a point where petrol production is in a domestic surplus. Any time the blue line is below the highest point of the green bars, diesel demand outstrips domestic production. Production and consumption of fuel is important but so are the direct emissions associated with their usage.

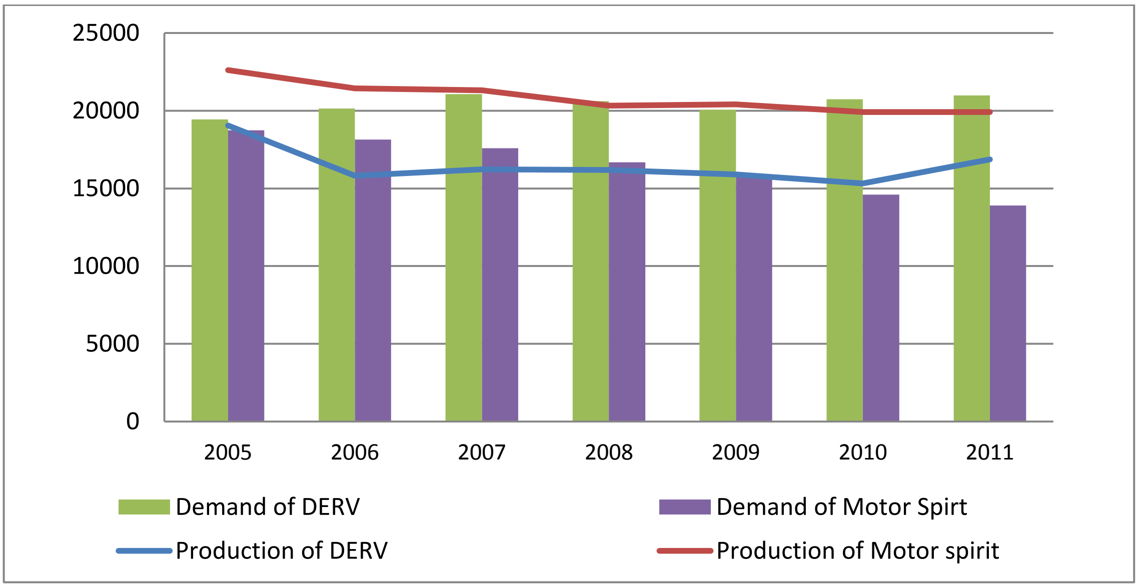

Figure 8 - Diesel and Petrol demand and production, UK, 2005-2011

UK CO2 emissions from petroleum products have been on a sharp decline since 2005. This has coincided with the switch to diesel fuels but has also indicated the overall greater independence from fossil fuels in the UK society. The following chart is a summarization of gross CO2 emissions from combustion by fuel type in the UK for the period 2000 to 2009.

The chart on figure 9 shows carbon dioxide equivalent (CO2-eq) emissions in megatons for the combustion of different fuels. The entire gross emissions due to combustions have decreased dramatically from a peak of 172.2 megatons in 2005 to 153.8 megatons as of 2009. This is a reduction of 10.7% and a positive sign that UK society is reducing CO2 emissions from fuel consumption.

The switch to diesel from petrol has also made a difference in the combustion emissions that each fuel is responsible for. CO2 emissions for petrol combustion dropped more than 27% from year 2000 to 2009, which is logical given the significant decline in petroleum consumption. Diesel on the other hand has increased CO2 combustions emissions by 28.5% in that same time period. The one aspect of this trend that is encouraging is a decline from 2008 to 2009. How much of this is related to the worldwide economic crisis is unknown due to the absence of more time-series data.

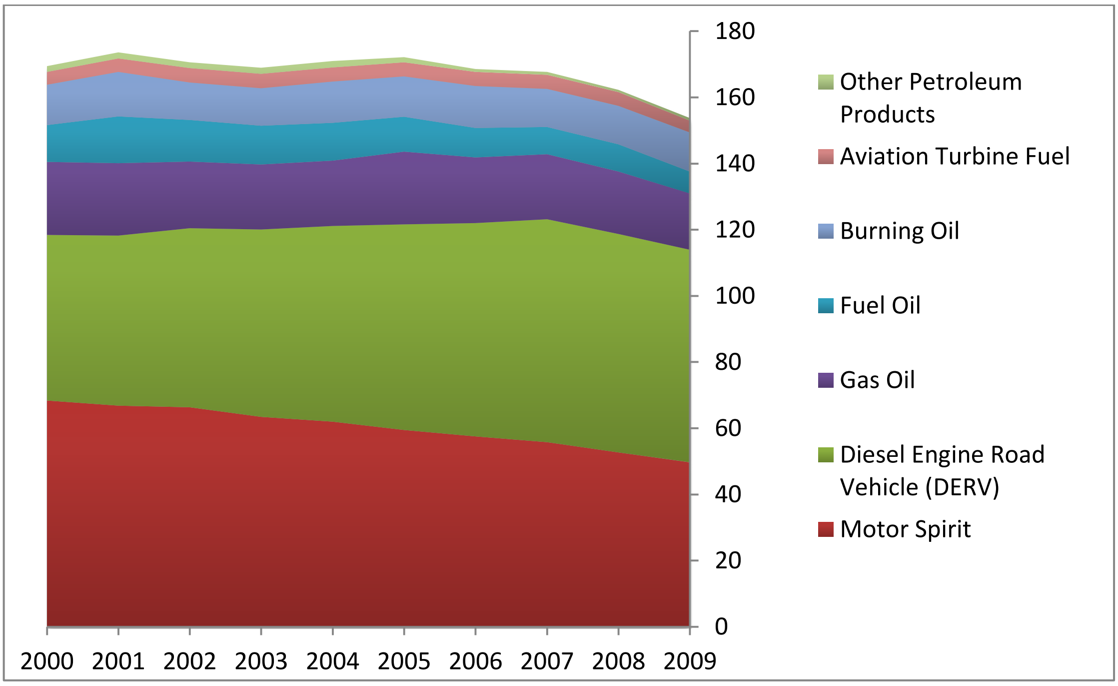

Figure 9 - Gross combustion emissions of petroleum fuels by type, UK, 2000-09

CO2 combustion emissions for all other fuels declined at a rate between 3% and 40.5% from 2000 to 2009. This trend could be indicative of many things including more fuel efficient engines, cleaner combustion technologies and an increase in the usage of collective transport. No matter the cause, this is excellent news for UK climate planners.

The emissions reported here are just direct emissions from combustion and do not include other emissions from the upstream processes. Understanding the refining picture becomes more important now that this base has been established. To answer the questions of how the UK is really doing with regard to fuel usage emissions, it is important to try and map the entire process chain. Refining is the second step on that chain.

The UK refining sector

There are currently 8 major refineries operating in the UK which comprise more than 97% of all refining capacity in the country. They are located in various regions of England, Wales, and Scotland as shown on the map. The net production of crude oil products, which is a measure of gross production less process requirement feedstocks and process losses, amounted to approximately 81% of total capacity for 2009. The chart below shows output as a measure of net output as opposed to gross output. The units for the capacity and output are in tons of petroleum product output (UK Department of Energy and Climate Change, 2009).

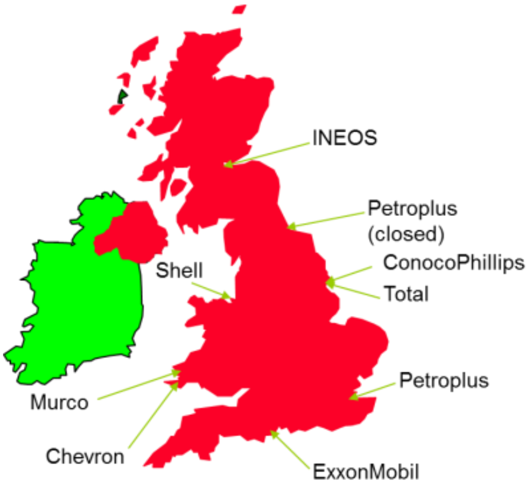

Figure 10 - Map of refineries in the UK

The largest refinery both in terms of output and in terms of capacity is Fawley, which is owned by ExxonMobil. The smallest refinery is Milford Haven, which has a capacity of 5.4 million tons annually and produced just over 4.9 million tons in 2009. The most complex[1] refinery is Pembroke, which is owned by Chevron. The average plant was operating at 81% capacity in 2009 (UK Department of Energy and Climate Change, 2012).

Refinery	Total capacity	2009 Output	Nelson Complexity
Stanlow - Shell UK	12 000 000	9 917 940	7,4
Fawley - ExxonMobil	16 000 000	13 162 449	9,1
Coryton - PetroPlus Intl.	10 000 000	6 710 317	8,3
Grangemouth - Ineos Refining	10 000 000	8 313 201	7,9
Humber - ConocoPhillips UK	11 500 000	9 301 251	5,9
Lindsey - Total UK	10 500 000	8 574 056	8,6
Pembroke - Chevron	10 500 000	9 605 330	11,3
Milford Haven - Murco Pet. Ltd	5 400 000	4 909 289	8,0
Total	**86 500 000**	**70 493 834**	-

Figure 11 - Statistical overview of UK refineries

Each of these refineries has a fixed output capacity, meaning that for every barrel of crude inputted, a certain product mix will be outputted. Refineries are generally forced to remain with fixed output unless configurations are changed. The more complex refineries have some flexibility in what they

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[1] Refinery complexity is graded by the Nelson Complexity Index, which is a measure of how much infrastructure, processing capacity, input capacity, differences in input crude, and ability to change outputs depending on input crudes and demand requirements. A more complex refinery is specialized and more flexible to choose inputs based on price and outputs based on demand to meet market requirements. It is advantageous in the refinery business to be flexible in the face of the global pricing of fuels (Reliance Industries Limited, 2009)

can produce but are effectively tied to their configuration until upgrades occur. This offers some economies of scale for the refining industry but that is only in the short term. If market conditions match the refinery configurations, profit margins can be healthy. More often than not, the fixed nature of production capacity causes refineries to be exceptionally vulnerable to dynamic markets and fuel price changes.

In the UK, price volatility caused the closure of Petroplus Teeside refinery in 2008 and could cause the possible closure of Coryton in the future due to market fluctuations and decreasing crude availability from the North Sea (Petroplus International, 2010).The pattern in the UK has been one of consolidation such that the 8 major refiners are not going to be challenged by the construction of any new refineries. Instead, it will be a struggle for the major refiners to remain economically viable.

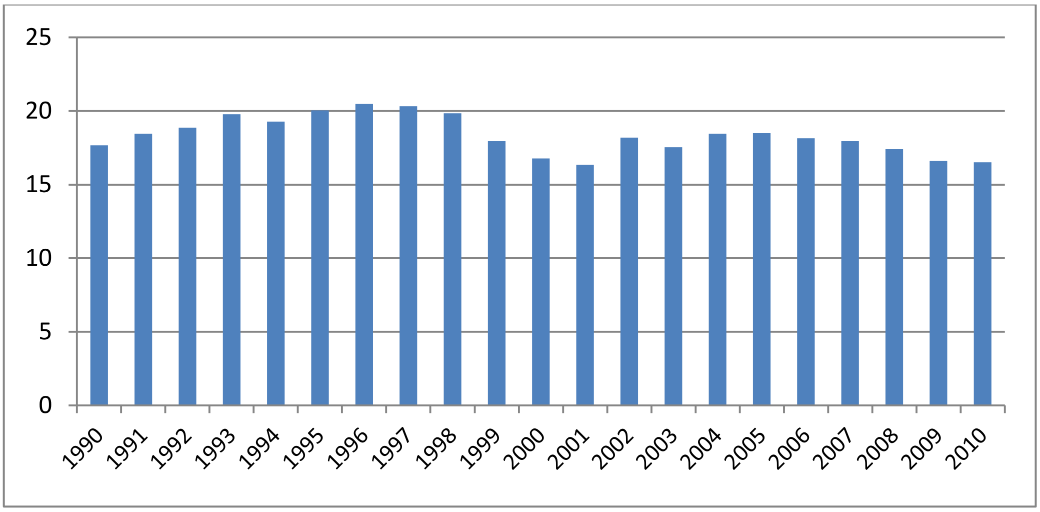


Figure 12 - Mt CO2-eq total for all refineries in the UK, 1990-2010

The market conditions notwithstanding, petroleum refining still constitutes a major source of air emissions in the UK. The direct process CO2 emissions as a sum of all refining operations have remained relatively constant over time peaking in 1996 at 20.3 megatons while reducing down to 16.5 megatons as of 2010. The following chart summarizes the CO2 emissions in the UK due to refinery production.

The pattern since 2005 is a slow decline of 2.0 megatons of CO2 emitted below 2005 levels, which is a 10.8% reduction of CO2 emissions from direct refinery processing. This is only direct process emissions and does not account for the other upstream processes that are required to supply the refining industry with infrastructure, energy, and other inputs. It is only a measure of CO2 coming from the plants due combustion. This can be improved upon by expanding the system boundaries to encompass other processes important to refining.

Expanding the system boundaries on UK refining

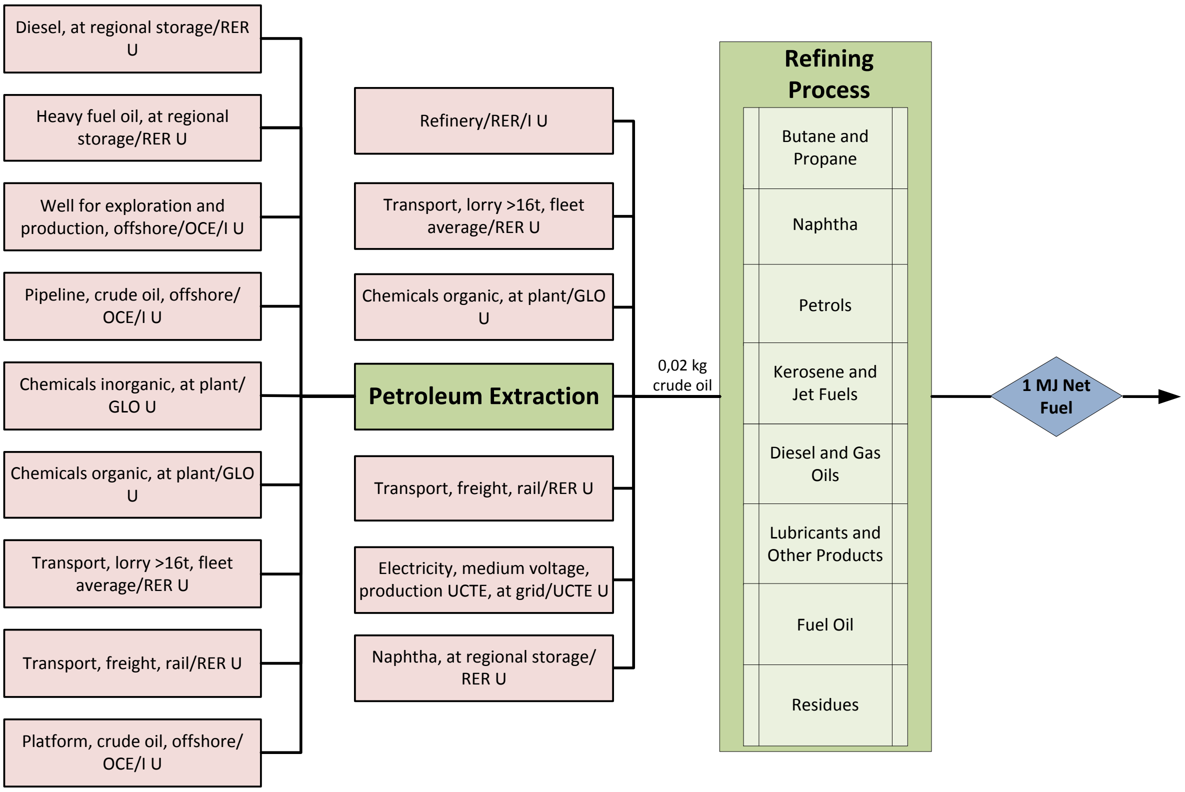


Figure 13 - Ground to Gate Petroleum Refinery Process Flow Diagram

The UK refining sector contributes emissions to the petroleum process chain, but in what proportion to the rest of the chain is unknown. The processes further upstream must be included so that a more robust model can be developed. It is worthwhile to map all of the upstream processes to refining because without the extraction and exploration for crude petroleum, there would be no need to refine the crude. This is the first step to mapping the entire petroleum process chain.

The process flow diagram of the refining industry is a visual representation of the petroleum refining process chain. The system boundaries are the point of extraction to the gate of the refinery. This includes exploration for crude in the form of exploration wells, transport from pipelines and to the refinery, the energy inputs required for both extraction and refining in addition to the chemicals used in both processes. The functional unit is 1 MJ of fuel output.

The extraction process is developed as closely as possible to the actual UK extraction system which encompasses peripheral inputs that contribute to the emissions of the process as a whole. The petroleum extraction process offers higher resolution than the refining process because more information was available and it is only a single process as opposed to containing a sub-process process chain like refining.

The refining process on the other hand is analyzed as a single “box” model where the sub-processes within this box are aggregated together. The sub-processes are the different processes described in the refining theory section of this paper. The box system for the refining process is helpful when many co-products are involved and when production and emissions data for the sub-processes is unavailable or of poor resolution. Thus the box model is advantageous not for discerning the emissions on each sub-process but rather can be used to look at the fuel types as a whole after allocation..

This system diagram above is actually the common, simplified system diagram for the 8 products in the refining process box. The products included in the analysis are *butane and propane, naphtha, petrol, kerosene and jet fuel, diesel and gas oils, lubricants and other products, fuel oil and residues.* These are the main outputs that will be analyzed for this case. With lubricants and residues, a nominal MJ value will be assigned as the use of these products is decidedly not energy based. Using 1 MJ as a functional unit for each fuel also allows the ability to compare emissions between fuel types.

The process flow diagram used in this case study forms the basis of the system being analyzed and provides the best resolution given the information available. It is a visual representation of what is being studied and represents a complete picture of UK refining and its associated upstream processes.

Research goals

The scope of the study has now been introduced. The next step is to identify specific goals of the study. The main goal of this study is to analyze the environmental impact analysis of petroleum refining in the UK. It is important to be able to separate emissions between each fuel type and with the full process chain from “ground to gate” included. To meet the main goal, a series of supporting and ancillary goals are identified to both ensure that the process is complete and useful for decision makers. The added value for decision makers comes in the form of additional scenario analysis and a scaling up of the results to compare with current UK figures.

To have a thorough and meaningful study, a series of objectives must be completed in an organized and time-ordered manner. The first objective is to compile air emissions data from each plant and then couple this with production figures from each plant to use for the lifecycle inventories. Each fuel in the study is analyzed and the environmental impacts organized according to production share. Supporting this is the compilation of macro-UK data so that plant level production and emissions data can be reconciled and validated before moving forward with lifecycle inventory (LCI) construction.

Where data on production is unknown, estimations must occur so that gaps are filled. The same is to be said about the emissions data in that all gaps must be reconciled and validated to match the macro UK production and emissions mix. The validation of this data is integral in providing results which are representative of the entire UK petroleum processing situation.

After validation of the UK production data and emissions data, the construction of multiple LCIs can occur. To supplement the data gaps for emissions and background processes, data from other sources is to be compiled and organized as they pertain to the main petroleum refining process. The compiled data must all be organized according to the functional unit of 1 MJ fuel output.

To compile the emissions data and appropriately assign emissions to specific outputs, allocation must occur. The best method for allocation must be determined and then utilized. When this allocation occurs, the individual LCIs based on each fuel type can be constructed.

The compilation of multiple LCIs for each of the multiple fuel types will be based on the average UK emissions per 1 MJ of each fuel type and will be coupled with upstream emissions information from extraction processes. Background data from the extraction process will be integrated into the individual LCIs to provide depth and scope to the petroleum refining process. Additional data on the background and stressor information will also be added from existing databases where data for this information is unavailable.

Following the compilation of the various LCIs, impact assessment calculations following lifecycle assessment frameworks will occur. These calculations will characterize impacts so that multiple environmental emissions can be plotted together in a relevant way for comparison. The calculations will be through the Leontif inverse method and will be calculated for each fuel type.

Once the impact assessment calculations are complete, the results can be scaled upwards to represent the entire UK petroleum processing industry. The scaled up results can then be compared to the current information available.

After the scaling and comparison, a modification on the LCIs for different production technologies will be organized. This process, called scenario analysis, will subject two refineries with different technologies to the rubrics of life cycle impact assessment in the same process as the UK average emissions per fuel type. The results will be compared on a per MJ out by fuel type to assess the differences. The differences in emissions will represent the technology decisions by each petroleum refiner.

The results of these impact analyses will then be compared with the results currently in the field. This process, known as benchmarking, will provide context to the results of the impact analyses. The results of this study must be justified compared to these results both quantitatively and qualitatively. The results will also be compared to a full lifecycle analysis of a particular product which uses petroleum goods so as to provide more context on the impacts of petroleum processing within a larger system scope.

Finally, the last step is a discussion of the results and what they imply for the research that exists, the decisions makers and the petroleum refinery operators. The results of this study are intended to add to the body of work that exists thus far and to create greater information for impact assessors concerned with the UK environmental emissions.

Methodology

Lifecycle analysis process

Life Cycle Analysis (LCA) is the deconstruction of environmental impacts by production tiers to determine where emissions are occurring within a process chain and how these emissions cause environmental stress. LCA is an attempt to first quantify emissions in standard categories and then establish meaning from the results to try to discern where tangible environmental damage is occurring and the resulting effect it will have on an ecosystem. A well-organized LCA can bring to light previously unknown sources of emissions to institute change in production behaviors to ultimately reduce environmental impacts. LCA helps to give a holistic perspective of a process and its impact on the environment.

The construction and execution of an LCA requires four steps of preparation, calculations and interpretations. The steps are: goal and scope definition, inventory analysis, impact assessment and interpretation. The first step is to determine which processes are going to be included in the system boundaries, known as the goal and scope definition. Inventory analysis is the following step after the goal and scope definition. Inventory analysis is the organization of all data relevant to the LCA and combined into a matrix called the process requirements matrix. Often before inventory analysis can be done, some calculations and conversions need to take place and data must also be sourced and collected. Inventory analysis usually involves compilation of information and data from multiple sources. The impact assessment follows inventory analysis and is a series of calculations which organize the impacts of each process in the LCI. Part of impact assessment can include building scenarios to compare results. Following the impact assessment is a discussion on what the results mean and what context they should be viewed.

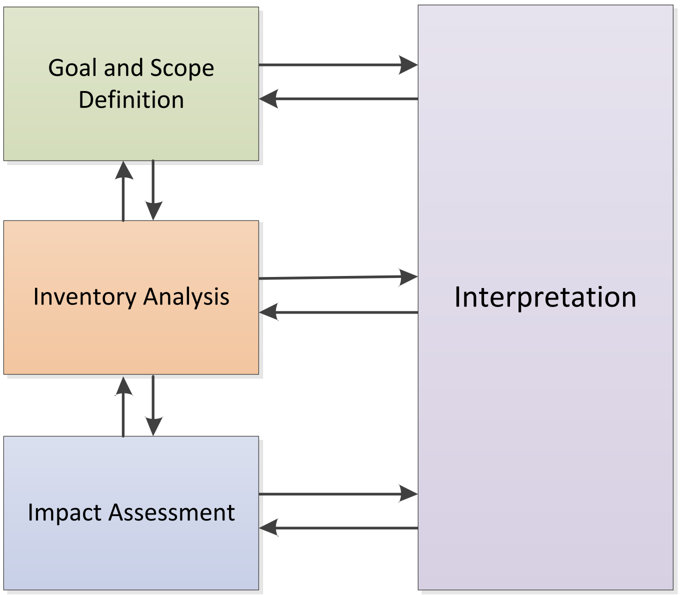


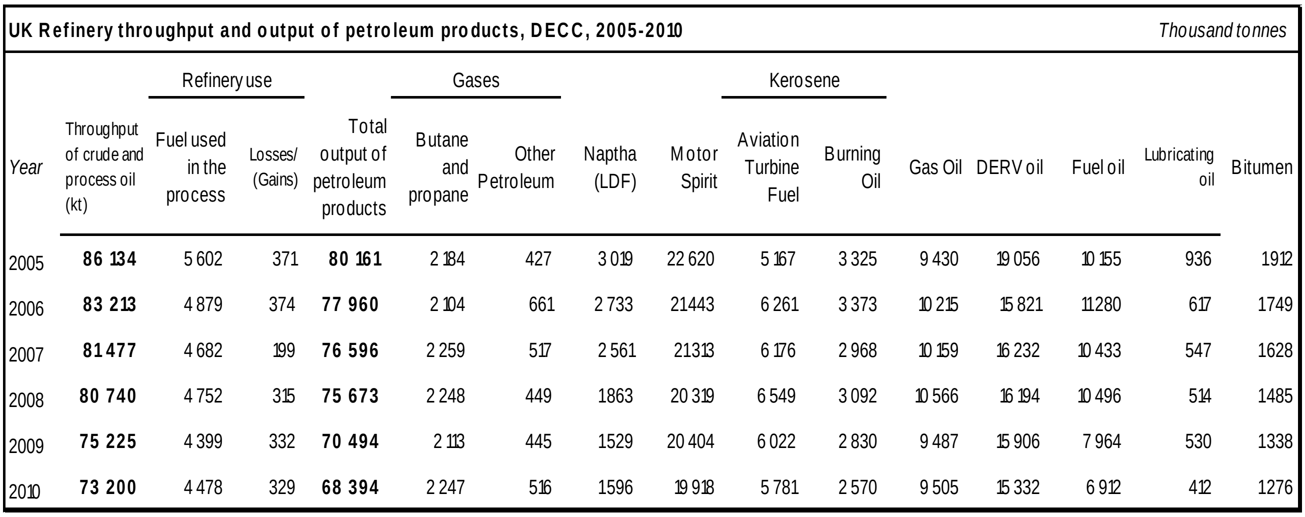
Figure 14 - Lifecycle assessment framework

The goal and scope definition for this study has already been discussed so the next step is the preparation and construction of the lifecycle inventory (LCI).

Lifecycle inventory preparation

The compilation of the lifecycle inventory (LCI) required two main bodies of information: emissions and production data. This information is required at a plant level to associate and assign emission shares to each fuel type based on refinery output. It also required at a macro level so that the entire UK refining sector can be analyzed. Additional information required for the compilation was commodity price data, average energy density of each fuel type, and background system information. The analysis and compilation will focus on data from 2009, as this is the most recent year where information is available with relatively high resolution according to the needs of the project.

The macro level figures were supplied by the UK Department of Energy and Climate Change (DECC). The DECC is a UK government agency which organizes statistics and reports on UK energy systems and air emissions. The DECC has macro level, time series information on overall UK production and only overall CO2 equivalent (CO2-eq) emissions for the economy on a sector by sector basis. The refined petroleum macro figures were also available on DECC and were organized by fuel type. A sample of this table can be found below.



UK Refinery throughput and output of petroleum products, DECC, 2005-2010 *Thousand tonnes*

Year	Throughput of crude and process oil (kt)	Refinery use		Total output of petroleum products	Gases		Naptha (LDF)	Motor Spirit	Kerosene		Gas Oil	DERV oil	Fuel oil	Lubricating oil	Bitumen
		Fuel used in the process	Losses/ (Gains)		Butane and propane	Other Petroleum			Aviation Turbine Fuel	Burning Oil					
2005	**86 134**	5 602	371	**80 161**	2 184	427	3 019	22 620	5 167	3 325	9 430	19 056	10 155	936	1912
2006	**83 213**	4 879	374	**77 960**	2 104	661	2 733	21443	6 261	3 373	10 215	15 821	11280	617	1749
2007	**81 477**	4 682	199	**76 596**	2 259	517	2 561	21313	6 176	2 968	10 159	16 232	10 433	547	1628
2008	**80 740**	4 752	315	**75 673**	2 248	449	1863	20 319	6 549	3 092	10 566	16 194	10 496	514	1485
2009	**75 225**	4 399	332	**70 494**	2 113	445	1529	20 404	6 022	2 830	9 487	15 906	7 964	530	1338
2010	**73 200**	4 478	329	**68 394**	2 247	516	1596	19 918	5 781	2 570	9 505	15 332	6 912	412	1276

Figure 15 - UK Refinery throughput and and output of petroleum products

(UK Department of Energy and Climate Change, 2012)

The plant level production information was organized from various annual reports and from information on the UK Petroleum Industry Association (UKPIA) website as well as statistical reports. This data was often found to be incomplete and required ancillary work. Most refineries reported a production mix in terms of capacity but not in terms of output, which meant that figures on total output mix were estimated. In half of the cases, overall plant production (overall refinery output) was reported, which could then be used to determine the product mix assuming that capacity production mixes and output mixes were identical.

Refinery	Product Mix Available	Plant Owner (2009)	2009 Output	Source(s)
Stanlow	Yes	Shell	Estimated	(Essar Energy, 2012), (Donovan, 2011), (UKPIA, 2011)
Fawley	Yes	ExxonMobil Co. Ltd	Known	(Esso UK Ltd, 2011), (UKPIA, 2012)
Coryton	Yes	Petroplus International	Known	(Petroplus International, 2010), (UKPIA, 2012)
Grangemouth	Yes	Ineos Refining	Estimated	(UKPIA, 2012)
Lindsey	Yes	Total UK	Estimated	(UKPIA, 2012)
Pembroke	Estimated	Chevron Ltd	Known	(Chevron Corporation, 2010), (Valero, 2012), (UKPIA, 2012)
Humber	Yes	ConocoPhillips UK	Estimated	(UKPIA, 2012), (ConocoPhillips, 2011)
Milford Haven	Yes	Murco Petroleum Ltd	Known	(Murphy Oil Corporation, 2009), (UKPIA, 2012)

Figure 16 - Refinery Output and Product mix, source of information

The production mix of Pembroke was relatively simple to determine given that the overall production mix of the UK economy was known and that the total output from Pembroke was known and reported. By having the full UK production figures by fuel types, the remainder not utilized in the production of the other plants would thus be allocated to Pembroke's production and a product mix of output could be found. The Pembroke plant product mix estimations were only counted as part of the greater UK emission results and were not used for any further analysis.

Estimating the additional output mixes were done on a basis of averaging the remaining output for the four refineries where output for 2009 was not found. The product mixes were available for each of the four refineries and were used to determine the output of each product type after the average output was calculated. The assumption that this makes is that there is a similar output to capacity ratio for each of the four plants with unknown outputs. These four plants were only counted as part of the greater UK emission results and were not used for any further analysis.

Plant level air emission information came from the UK National Atmospheric Emissions Inventory (NAEI). The NAEI organized air emissions data into nearly 50 different categories on a plant level. Each refinery is required to report emissions to the NAEI which were then published on a publicly available database. There is no distinction on whether the emission reported came from a particular process within the refinery (i.e. fractional distillation versus vacuum distillation) and thus required allocation between the products, which will be discussed further in the next section. The breadth of this data allows for the LCA to provide more complex information on emissions to air in the UK than previously analyzed (AEA, 2009).

Emissions to water are not reported in the UK. All water emissions used in this case come from the EcoInvent database and are included to offer completeness to the LCA study as opposed to presenting fundamentally new and interesting results. Other background system data came from the EcoInvent database and were again included to offer a more complete picture to the processes involved in refining if not offering fundamentally new information. EcoInvent data was also used for benchmarking the results with the current state of the field (Frischknecht, 2007).

Commodity price information came from the Organization of Petroleum Exporting Countries (OPEC) while average energy content for fuels (calorific values) came from the DECC (UK Department of Energy and Climate Change, 2009) (OPEC, 2009). Both price and energy content is necessary to be able to allocate emissions by refined fuel type and to be able to compare different fuel types with one another when end results are calculated.

Finally, the last core dataset comes from an internal study at NTNU which examines the UK petroleum extraction sector. The extraction of petroleum fuels captures all of the emissions related through the whole petroleum process chain from extraction to refinery gate (Pak, 2011).

For the scenario analysis, the same data from the main study is used except the focus is on the individual plant production figures instead of UK average figures. Each plant is characterized by differing technologies. Energy for Coryton comes from a 779MW gas powered electricity plant attached to the facility (UKPIA, 2012). The Fawley plant utilizes combined heat and power within the refinery to achieve upwards of 75% efficiency (Esso UK Ltd, 2011). Additionally, each plant has a similar capacity for cracking and conversion and reforming capacities. The major difference between plants is that Fawley has a larger capacity but the product mixes are very similar. Only Coryton has less net output of light natural gases and feedstocks because Coryton uses the output to feed into the gas powered plant.

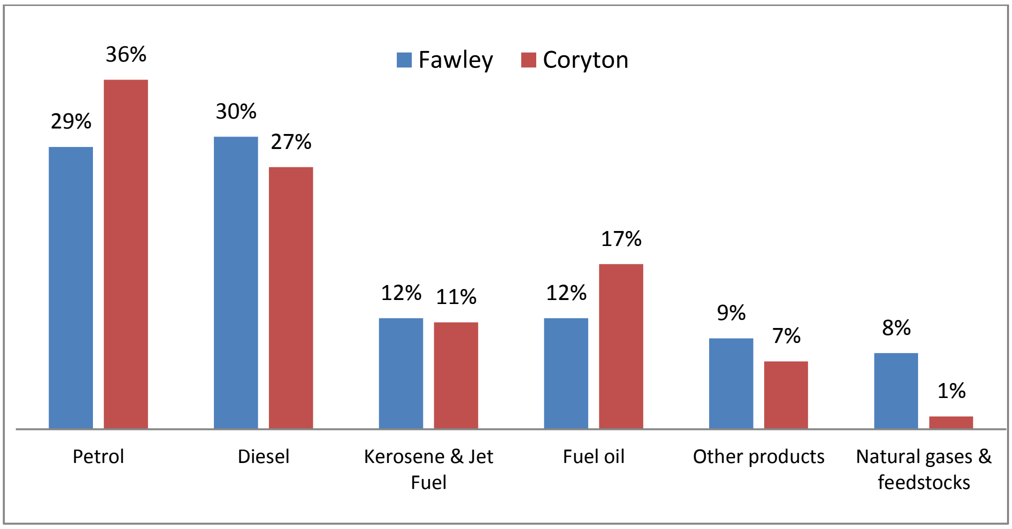
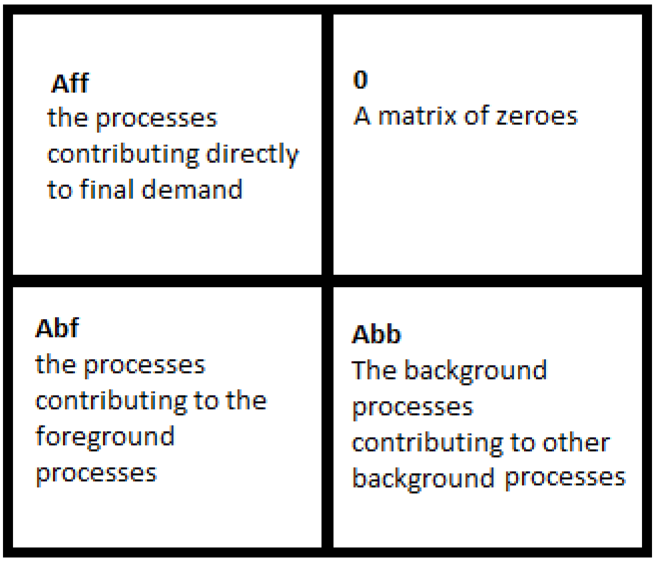


Figure 17 - Fuel output mix, scenario model refineries

(UK Department of Energy and Climate Change, 2012)
The similarities in output allow for a basis of comparison between the two plants. Additionally, these two plants required no estimation on outputs reducing the uncertainty of the product mix. These two plants make perfect candidates for scenario analysis.

Lifecycle inventory analysis

Inventory analysis is the second step in organizing data for a lifecycle analysis study. An inventory analysis is an organization of all available data into categories that will be used to create a lifecycle analysis. The order in which this data is organized is not necessarily critical to the outcome but it must be organized in terms of the final demand unit, in the case of this study, per MJ and must include data relating to the foreground (direct processes), background (indirect processes related to foreground processes) and environmental stressors relating to the direct processes. The common way is to organize the production data in a form such that one can take the visual process flow diagram and place it into a system of matrices. This system has the foreground in the upper left quadrant labeled as *Aff*, the background system in the lower left quadrant labeled as *Abf,* and the background to background system labeled as *Abb.* The Abb matrix is not of any concern for this study. The total of all these matrices is known as the *process requirements matrix*, denoted from now on as the A matrix.



Aff the processes contributing directly to final demand	**0** A matrix of zeroes
Abf the processes contributing to the foreground processes	**Abb** The background processes contributing to other background processes

Figure 18 - Process requirements matrix

Setting the system boundaries

The A matrix is a mathematical representation of the process chain and contains all the processes included within the system boundaries. In the case of the Aff matrix, there are two main processes included: Petroleum extraction and refining. The petroleum extraction is organized on information from a previous study at NTNU while the refinery process is the focus of this study.

Determining the system boundaries for refining is based on the resolution of data available, the processes known and the allocation of the processes depending on what products were outputs. The refining process is a complicated one as explained in the theory and from looking at the resolution of the data; a decision was made to aggregate all of the refining processes together into a single “box”. This box includes all processes related to refining. The data that was available for emissions did not include any information on which processes were causing which emissions. The data available was emissions per plant and when plant output is known, allocation can fix the box system problem for assigning emission shares.

The process to determine refinery output was not as clear cut as it could be. The production output of refineries is protected information. Each refinery is not required to publicly release the production data and only are required to submit data to the DECC for compilation of national figures. This poses a problem for determining the output mix of production. Fortunately, all refineries but one releases the average product mix, which is available from UKPIA. This production mix is fixed given refinery configuration and can change when infrastructure is changed. For the purpose of this study, the assumption is that the product output mix from UKPIA is the fixed output mix for each refinery. The only refinery to not have this output mix was the Pembroke refinery.

It was possible to determine individual refinery outputs by using the mixes from UKPIA, however not every refinery had reported output. *Stanlow, Grangmouth, Killingholme/Humber, and Lindsey* required the use of estimates to determine product output. The other four refineries had reported their total refinery outputs so that 57% of the refinery output was accounted for. The other 43% was apportioned based on a few factors. The estimation for production was simply a division of the unaccounted production based on total refinery capacities. As an example, Stanlow has a capacity of 12 million tonnes crude throughoutput annually while Grangemouth has a capacity of 10 million tonnes. Thus a proportional splitting of the remainder was necessary. This proportional splitting was also modified as total production required a scaling down of the naphtha output for all refineries that produced naphtha so that all estimated refineries had similar but not the same estimated output percentage. The assumption is that these plants are producing at these estimated rates.

The reason for scaling down output for naphtha was because naphtha is a petroleum feedstock first and foremost. It has little commercial value outside of a feedstock for refineries and is thus used in this way. The method of determining exactly how much product was produced in each plant involves simply multiplying out the mix of each refinery (from UKPIA) by the total net output of the plant. Unfortunately this method produced an over-estimation of naphtha products when scaling up to the entire UK output of naphtha and comparing it to a scaling up of naphtha production from the estimations. The scaling-down affected plants that had a higher proportion of naphtha to skew the total production slightly lower so that the estimates which should have been equal percentage outputs were otherwise slightly unequal. The assumption that is made is that the extra naphtha being produced goes back into the refining processes as a feedstock and may even be sold between plants. The emissions associated with the additional naphtha consumption are embedded within the refinery box model.

The comparison of overall DECC figures on production proved very useful in modeling output properly and especially when modeling the output of the Pembroke plant. The total product output of Pembroke was found while the product mix was not known. This saved a lot of work and estimations because the total output of all fuel types from all other plants combined were subtracted from the DECC totals for all fuel types. The remainder of this constituted the Pembroke refinery output and was organized by fuel type to give a product mix and output mix for Pembroke. In addition, an assumption was made that Pembroke had no naphtha output so as to make the scaling calculations simpler. The net throughput of petroleum products for Pembroke was known and the remainder balanced with the DECC figures when naphtha was scaled down proportionally. The assumption made is that the Pembroke plant produces output with these proportions, which may very well be true but given the additional estimation of output, not entirely likely.

The national figures are not a good base to compare production figures with each plant. When all the plants are summed together the national figures provide a basis of comparison. The national figures must be the same as the aggregation of all products in the study. In this case, the DECC national production figures balanced with the figures on production, including the estimates and scaling. The plant figures are important so as to give context to production and add great resolution to the impacts of outputs. The aggregations are useful once emissions are allocated.

Following the work with the production data, the emissions data had to be organized by plant. The air emissions of each plant were reported and known for all plants for 46 air emission categories with one exception. The CO2 released by the Grangemouth refinery was not reported and when all other emissions were summed, they did not match the DECC figures. To fix this, all the reported CO2 emissions from the other plants were aggregated and subtracted from the DECC reported figure for the entire UK. There was no estimation to decipher the CO2 emissions for Grangemouth. It should be noted that these are only the direct process emissions for the year 2009.

Environmental emissions must be divided between production outputs in cases where there are multiple outputs. This division is known as emissions allocation. The emissions data organized by NAEI for each plant were not allocated according to production process or output mix. Within the box model for the refinery process, the allocation could not take place between processes so allocation between different outputs was required. There are three main methods with which allocation of emissions for refined petroleum products: *mass allocation, energy allocation and economic allocation*.

Mass allocation is the simplest form of allocation and is accomplished by dividing emissions by the physical mass quantity of outputs. This would make the assumption that all fuels have an equal emissions intensity per unit produced. This does not take into account the processes involved nor the potential work that each fuel or output can produce. In the refinery case, equal emissions intensity would be given to naphtha, which requires no further processing, to that of petrol. Allocating by mass in the box refinery process makes little sense because even just understanding the multiple refinery processes within the refining theory section would indicate that this is an inaccurate assumption and not suitable for the study.

Energy allocation assumes that emissions can be allocated by the energy content of the different fuels. This can be a good way to allocate emissions when the outputs are clear and the processes known but are not necessarily reflective of the economic reasons for production. Energy allocation also struggles to assign emissions to non-energy products.

Economic allocation is a separation of emissions by market value of the products. This is done when the main goal is to determine which output is driving the need for production. In the case of petroleum refineries, the main drivers for production would not be a product like bitumen or naphtha because they are not going to produce the most income. Instead, petrol or diesel fuels, which have the highest economic value according to market value are the fuels driving production. Economic allocation considers that without the added incentive to produce a product of high value, production of the other co-products would not occur.

For the box refinery case, economic allocation is the best method of organization because it reflects the market conditions and reflects the ambitions of refineries to profit based on these conditions. It is also a fair comparison between different refineries as it can be used to gauge environmental efficiency, compare technologies and generally add greater value to the derivative works of the LCA study as will be shown with scenario modeling later. For this study, economic allocation was chosen. Prices for the economic allocation come from OPEC and are based on year end 2009 prices.

Separating emissions out by each plant

The economic allocation was performed at an individual plant level which organized the emissions in such a way that each refinery had a certain share of its emissions go to a certain fuel type. An example of this is to take refinery A that produces 32% of its revenue from petrol and assign 32% of its emissions to that fuel. It is a simplification but encourages the disclosure of different emission levels based on different production outputs. That is to say that the emissions from Plant A per unit of petrol may be higher than Plant B, which may produce the same amount of total petroleum products but only 28% petrol. This suggests that Plant A relies more heavily on petrol production to make revenue and thus the emissions will reflect the drivers of production. The end result is a summing of all emissions from each fuel type into separate categories.

The summing of all the emissions for each fuel type from the different plants set the stage for calculating the entire UK average for each fuel type. The next step was to take these summed emissions and organize them according to the functional unit of 1 MJ. To do this, each mass of fuel had to be converted to an energy value. The goal is to produce a total value of MJs for each fuel type then divide the emissions of each fuel type by the total MJ value to arrive at an emission per MJ value. The emission per MJ value can be inputted directly into a stressor vector that links emissions to the direct processes that cause the emissions. The calorific values of each fuel were provided by the DECC. The NAEI air emissions data had nearly 50 different categories of air emissions for each fuel type. These air emissions data were incorporated into the stressor matrix inventories as direct stressors to the foreground process.

Product	Net MJ per kg, DECC	Nov.2009, US$/ton, OPEC
Butane and propane (LPG)	45,9	$ 673,32
Naphtha	45,4	$ 673,32
Jet fuel	43,9	$ 670,36
Petrol	44,7	$ 714,91
Kerosene	43,9	$ 670,36
Gas/diesel oil	42,5	$ 603,68
DERV	42,9	$ 603,68
Fuel oil	40,7	$ 492,43
Non-fuel products (notional value)	40,9	$ 455,26

Figure 19 - UK Fuel prices and calorific values

(UK Department of Energy and Climate Change, 2009), (OPEC, 2009)

The life cycle inventory and emissions compilation was completed for a total of 9 separate fuel types: *petrol, diesel, jet fuel, kerosene, butane and propane, naphtha, gas oil, fuel oil, and other products*. The UK DECC production figures classify 11 types of fuels and products. Bitumen and lubricating oils were aggregated together into other products while the DECC category “other petroleum gases” was aggregated as a part of butane and propane output. Product prices were not fully available so some products share the same price as they were organized within fuel that are used for similar purposes or have a similar carbon chain. A summary of fuel prices and calorific values is found in figure 19.

Emissions to water are unfortunately not publicly reported in the UK. To fill in the gaps of the model, water emissions data was organized from the EcoInvent refining processes. The water data was used to provide a complete picture of the fuels being processed but is by no means the core value added processes of the study. The water emissions were added for the sake of having a complete model.

The background data used in the system for the refining process were also taken from the EcoInvent database. The processes required some modification to exclude background processes related to the combustion of process fuel, which are the primary emissions from the NAEI data. Integrating the background system with the NAEI provides a complete lifecycle model for the refining process that critically includes infrastructure, chemicals used in the process, transportation to refinery, and process fuel requirements. This EcoInvent data was utilized due to the unavailability of other data pertaining to the background system and again was used for the sake of a complete lifecycle model. In total, there were on average 40 separate background processes in each LCI. The EcoInvent database reports fuel output in kilograms so all background values were converted to per MJ values. The assumption is made that the EcoInvent data is the best representative data available.

The addition of the foreground process for the petroleum extraction comes from a study out of the Industrial Ecology Department from Norwegian University of Science and Technology in Trondheim, Norway on UK crude petroleum extraction (Pak, 2011). The decision to integrate the data into the model was to complete a process chain from the point of extraction to the refinery gate as an ongoing project within the department. The data itself differs from EcoInvent data and other data because it is specific to the UK petroleum sector and updated to current emissions. The background and emissions data related to the petroleum extraction process were taken directly from that project and used in this study. The study reported values in per kg crude extracted. The foreground process leading from extraction into the refining process was modified to be 1 MJ of crude as the required feedstocks were already included in the background system. Each of the petroleum products utilized the exact same extraction process as crude oil is the input for all fuels. The assumption in using this data is that the UK crude petroleum extraction study was complete and reliable enough to be used in this study.

The scenario models between the Fawley and Coryton refinery were organized in the same way as the main study. The emissions from each refinery were organized according to economic allocation for the output of products. The other emissions on the stressor vector, namely water emissions, were organized again from the EcoInvent database. The background systems were the same as the main study except that the Fawley refinery had modifications to the electricity required to use CHP as a component for 75% of electricity. The assumption made here is that the 75% efficiency reported is the correct figure. The CHP electricity figure came from EcoInvent. The foreground extraction process was the exact same as the main study as well. The model also follows the same box model for the refinery process. This is again due to unavailable resolution. Thus the differences in emissions are modeled on fuel outputs. There were only five main outputs from each plant and they were *petrol, diesel, kerosene/jet fuel, fuel oil, and petroleum gases*. The functional unit for each of the scenarios was again 1 MJ net output of fuel.

Impact assessment

The next step after completing an LCI is to begin with the impact assessments. Impact assessment is organized according to a few mathematical principles. The construction of the LCIs allows the processes and impacts from the entire chain be modeled mathematically. The use of matrices in the right form makes the impact assessment calculations simpler and more complete. As part of the LCA framework, the methods have a specific order with specific outcomes.

The foreground processes were first linked to a new stressor matrix based on the per-unit emission calculations. The main foreground draws upon the information set up in the background system and stressor vectors. The UK average refining process emissions and extraction emissions were inputted into two separate stressor vectors and then linked together. The EcoInvent data was also used in the stressor vectors to fill gaps where necessary. This was organized so that more than just the direct refinery emissions were measured.

The compiled LCI information must go through a series of impact assessment calculations to be a complete LCA. NTNU has a front end software program based on a MatLab GUI called ARDA, which does all the calculations and structural path analysis. The ARDA software provides mid-point environmental indicators that are characterized. The characterization allows a summing of all environmental impacts to a relevant figure that is comparable and complete. Characterization allows for many different stressors to be assessed together and simplifies the results. This is one of the advantages of using LCA and the ARDA software.

The LCA calculations that ARDA performs follow a standardized format for impact assessment. The model makes use of the Leontif inverse to facilitate calculation. As previously discussed, the process requirements matrix, denoted as A, is the recipe for production. The A matrix is a measurement of how much of a process is needed for one unit final demand output. In this study the final demand is 1 MJ of fuel output so the A matrix is organized in such a way to reflect the requirements per 1 MJ refined fuel output. The inputs to the final demand consist of the direct inputs to the refinery process and the background processes are drawn into the system as inputs to the foreground processes.

The total output is represented by the equation:

$$x = Ax + y$$

Where x is total output, A is the inputs to the process (the process requirements matrix), and y is the final demand (or external demand).

From this equation, it is possible solve for the unknown value of total output, x.

$$x - Ax = y$$

$$x(I - A) = y$$

$$x = (I - A)^{-1}y$$

$$L \; = (I - A)^{-1}$$

L is known as the Leontif inverse, where impact assessment uses the equation x = Ly. The L matrix is equivalent to the required outputs of processes i required to meet the final demands of j. In other words, l_{ij} is equivalent to saying the amount of output process i required to meet demand of j. For the study, y = 1 MJ refined fuel output.

From this structure, the emissions vector can be determined, denoted as e.

$$e = Sx = SLy$$

S is the stressors load, which is the units of emissions per output x. The next step is to diagonalize the output, x, so that:

$$E = S\hat{x} = \; S\widehat{Ly}$$

Diagonalizing will break down the emissions by separating each process. However, the LCA calculations undertaken are more interested in what happens with e. The vector e is only a measure of the emissions and can often be quite large with many different categories.

To be able to compare all the measures, a contribution analysis must be done. The C matrix is called the characterization matrix. Its purpose is to unify different emissions into standard categories. For example, the C matrix will convert methane and NOx into CO2-equivalents so that the total effect they have on the climate can be measured in a standardized form.

To standardize the emissions into impacts, C and e are used together so that the vector d can describe total impacts by impact category.

$$d = Ce = CSx \; = \; SLy$$

Using this and then diagonalizing x will calculate which impacts come from which processes.

$$D_{pro} = CE = CS\hat{x} = S\widehat{Ly}$$

The final step in the LCA process is the the interpretation. The interpretation of results begins with results presentation. All relevant figures are mapped with different graphing techniques with an emphasis on emissions to air. The discussion of these results follows.

Results

The results of this study are categorized in such a way that there will be two main bodies of results. The results of the LCI calculations, which reveal the scope of the LCA calculations will come first. The second set of results is the results for the impact assessment calculation for the main study and the related scenarios. A third body of results is the comparisons between the study and other known research figures. The main emphasis of all results is the emissions of CO2 and equivalent gases into the atmosphere from direct and upstream processes. The results are organized per unit and also scaled for the entire economy.

The first results are not results per se but the examination of the UK refining industry production and emissions as reported from the DECC.

Refinery level emissions and production results

The first result, shown in figure 20, is the fuel mix as given by DECC in the UK. This information comes from the year 2009 and is a measure of production in terms of thousand metric tons, or kilotons. The UK refining industry is most reliant on the large scale production of petrol (reported as motor spirit) as the prevailing pattern in the past was the large scale usage of petrol as the main transportation fuel.

Petrol production constitutes more than 29% of UK refined petroleum products in terms of net output. This is the largest share of output and more than provides for the domestic consumption. In fact, the UK is a net exporter of petrol. The production of diesel fuel (DERV) is the second largest portion of refinery output constituting approximately 23% of all refining output. Given the increasing consumption of diesel fuels in the UK for personal transportation, the country is actually a net importer of diesel despite substantial domestic production.

Gas oil, a product with a similar carbon chain to diesel is the third most produced fuel at approximately 13% while fuel oil is approximately 11% of total production. There is unfortunately no resolution given on the different gas oils and fuel oil types. The most common usage of these fuels comes in the form of home and commercial heating and as ship transport fuels. There is a steep drop off in fuel production with aviation turbine fuel (jet fuel) being the fifth most produced fuel commodity. The other fuels produced are not as important to the UK market as the top 5 and are usually considered less important for refinery production.

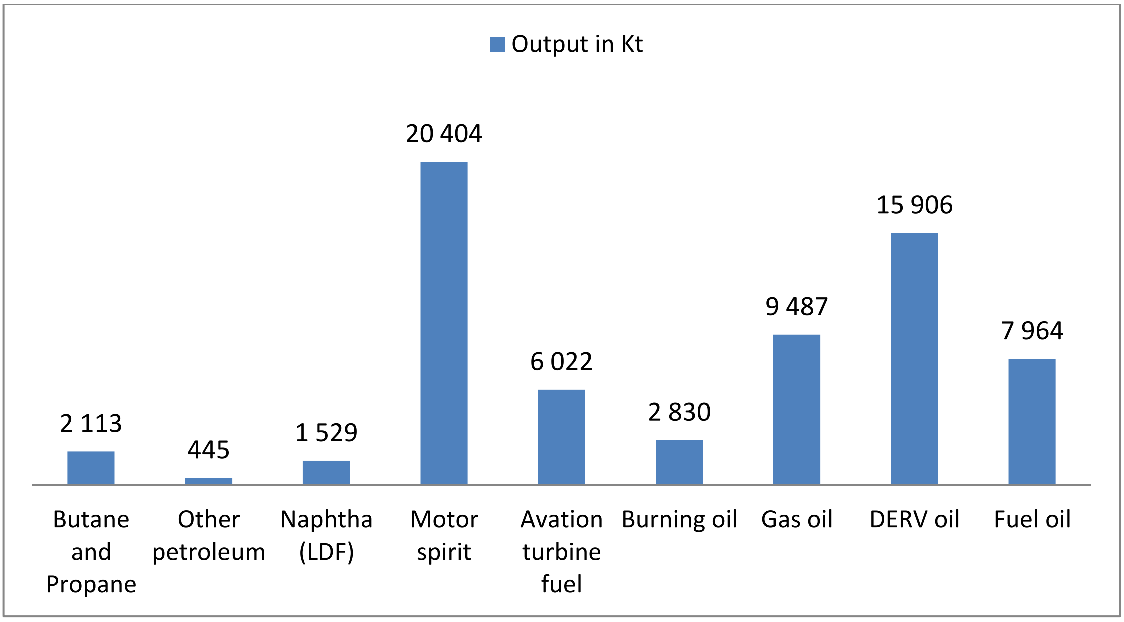


Figure 20 - Proportion of fuel output, UK, 2009

(UK Department of Energy and Climate Change, 2012)

Naphtha is a petroleum feedstock thus what is reported here is net output, not gross output to market. Most of the naphtha produced is used in the refining process so the figure of 1529 kilotons naphtha produced is the excess naphtha in the market as opposed to how much is actually used. When comparing the production of each plant individually, the naphtha totals are much higher than what is reported here but what their production does not account for is how much naphtha actually makes it to market. This was rectified with a scaling of fuel production for refineries that produced naphtha so as to fit the national output.

Regarding the net output of refineries, over the period 1995-2011, the refining process usage of fuels has declined. The efficiency of production, a measure of total throughput divided by total output from refineries (net output) expressed in terms of percentage has improved in the period 1995-2011. This is expressed on figure 21.

On the left axis is Kt of petroleum produced while the right axis is the efficiency, a measure of net refined petroleum output divided by crude petroleum input. The trend has been increasing process efficiency over time but how that will continue over time remains to be seen. There is a limit to efficiency. The interesting figure to note is that a similar peak of efficiency took place during the last major peak of production in 2004. As the reserves in the North Sea decline, refiners seem to be trying to improve the efficiency of their refineries to maximize the output that can be produced.

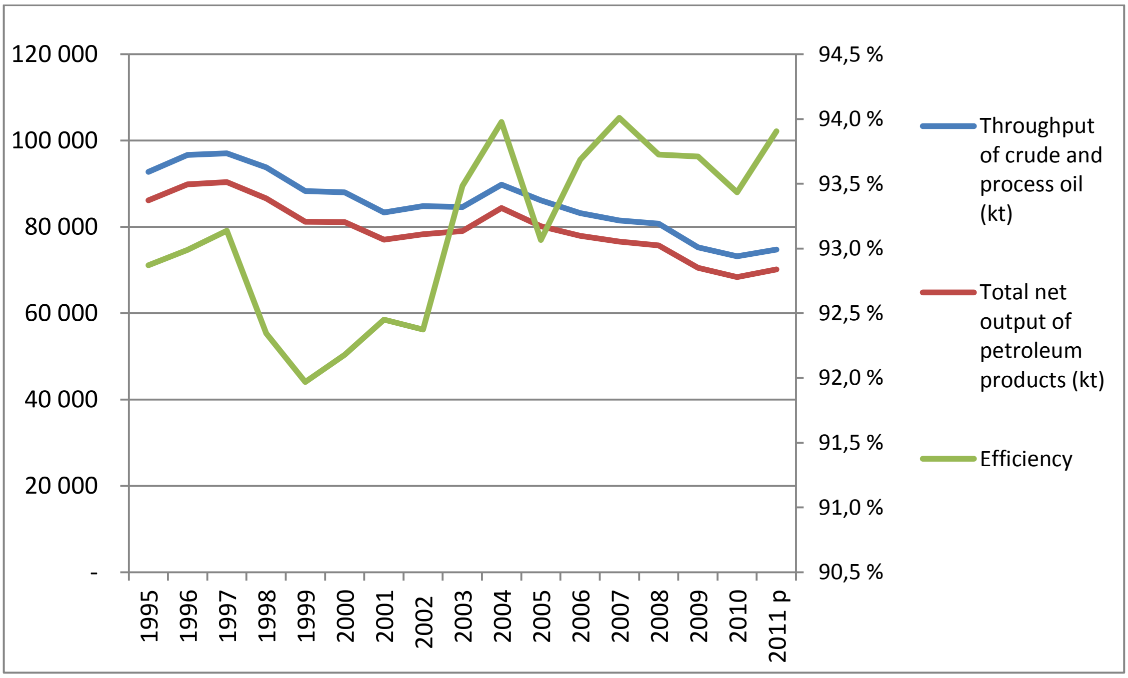


Figure 21 - Petroleum production in the UK, throughput and net output, 1995-2011

Figure 22 is an examination of the figures for petroleum products refined and emissions per kg. The units for this chart are grams CO2-eq per kg of refined fuel. This is a characterization of CO2-eq producing emissions from the NAEI emissions per refinery. The productions figures for net production at each refinery were the denominator and compared across all refineries. The production figures used are an aggregation of all fuel types combined in mass.

The production of CO2-eq emissions was highest at the Stanlow plant which curiously is neither a complex refinery with Nelson complexity index number of 7.4 nor is it a small refinery (implying that economies of scale should provide more efficiency). Milford Haven is the smallest refinery and has a below average emissions per output while Killingholme has the highest capacity for additional processes (with 9.5 million tons capacity annually for cracking and conversion) yet has the second smallest emissions intensity.

Without accounting for technology, the results offered here are less meaningful because each refinery has different production configurations. As a rule of thumb, the more complex refineries have more processes involved. While this does not directly imply that emissions would be higher for a more complex and process intensive refinery, it would make sense if that was the case. The next chart offers an index for emissions intensity which removes the technology complexity.

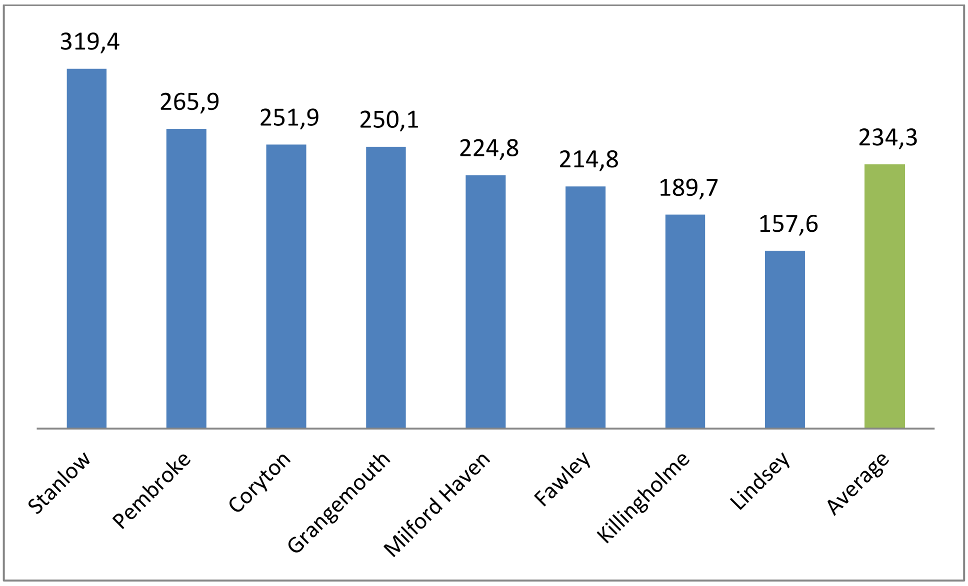
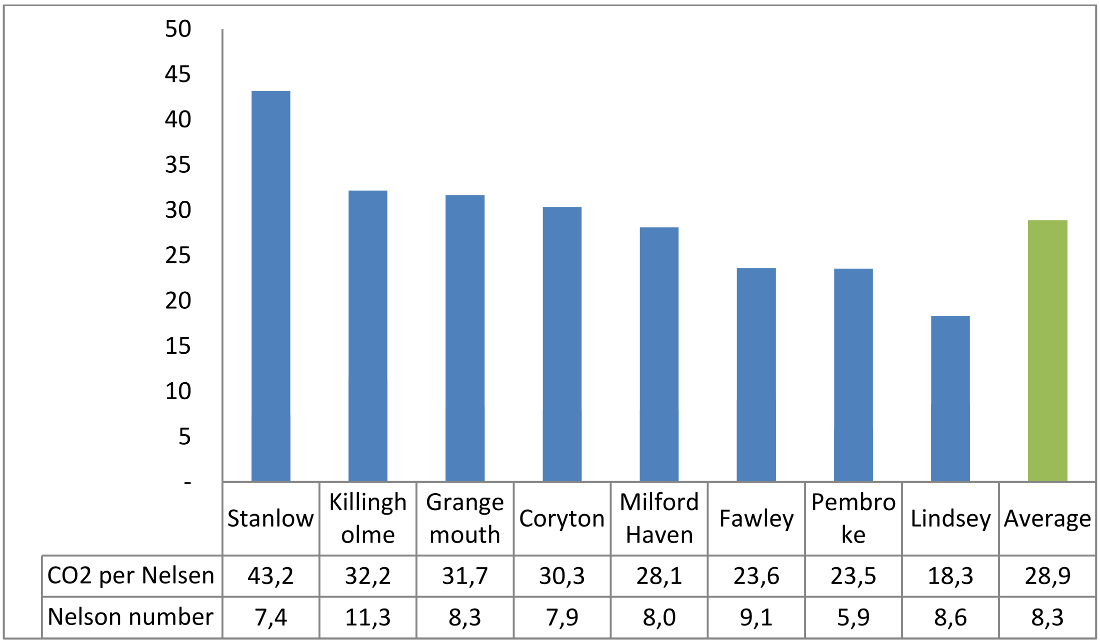


Figure 22 - g CO2-eq per kg refined fuel, by refinery 2009

The Nelson number is an index that measures the refining complexity of refineries after the primary distillation process. More weight is given to secondary refining processes such as vacuum distillation, catalytic cracking, reforming, etc. It offers a measure of comparability over different refineries when different configurations are not comparable (Reliance Industries Limited, 2009). In the UK, the average Nelson figure is 8.3 while the lowest is 5.9. The highest in the world for comparison sake is 14.6 while the highest in the UK is Killingholme at 11.3 (AEA, 2009) (UK Department of Energy and Climate Change, 2009).

Figure 23 is a measure of CO2-eq per kilogram of net refined fuel divided by the Nelson complexity number of the refinery. This is a useful measure in that the Nelson complexity number can adjust emissions per unit output for technology utilized. The point of this chart is to examine the environmental efficiency independent of technology and the results are similar in that the Stanlow refinery has the highest g CO2-eq per kg fuel refined. Stanlow tops the category in both straight emissions per kg fuel and Nelson adjusted g CO2-eq per kg fuel output. What this suggests is that the Stanlow refinery is a very poor environmental performer. It has a below average Nelson number and an above average adjusted CO2-eq emission.

Strikingly and not surprisingly Killingholme, by far the most complex refinery in the UK has the second highest Nelson adjusted emissions per kg output. Besides Stanlow, most of the other refineries are near or well below the average adjusted CO2-eq emissions.



	Stanlow	Killingholme	Grangemouth	Coryton	Milford Haven	Fawley	Pembroke	Lindsey	Average
CO2 per Nelsen	43,2	32,2	31,7	30,3	28,1	23,6	23,5	18,3	28,9
Nelson number	7,4	11,3	8,3	7,9	8,0	9,1	5,9	8,6	8,3

Figure 23 - g CO2-eq per kg net fuel ouput per Nelson Index number

Notably, the Lindsey refinery is very low on the adjusted scale even though the refinery has a slightly above average Nelson number. There also appears to be no general correlation between refinery complexity and emissions. However, this may be a false assessment as some refineries had estimated production figures.

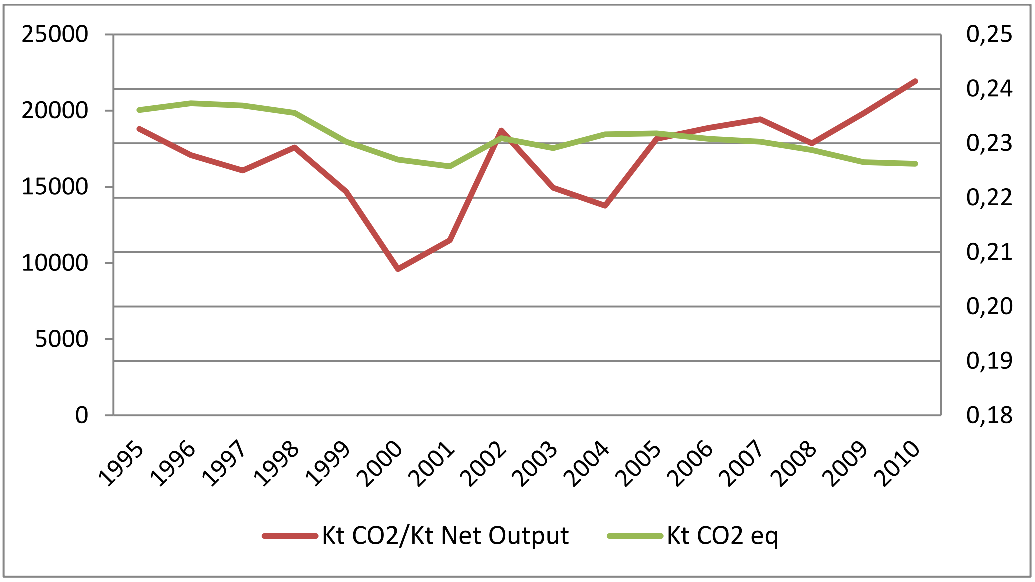


Figure 24 - Kt CO2-eq and kt CO2-eq per Kt net refined fuel, 1995-2011

(UK Department of Energy and Climate Change, 2012)

To fully appreciate the current situation in the UK, individual refinery emissions are not as relevant as the total emissions. The summation of the entire UK refining in figure 24 describes the environmental efficiency on the right axis as a measure of CO2-eq produced (in Kt) per unit output over the period 1995-2010. The left axis is a measure of total CO2-eq from the refining industry over time in Kt. The emissions figures and production figures are from the DECC.

The environmental efficiency is trending towards reduced output of CO2-eq per unit of refined fuel. This is a simple marker for the direct process emissions but do not explain the entire process chain. The signs are encouraging, however, that the UK refining industry is reducing process emissions overall but discouraging in that emissions per unit produced are increasing.

Impact assessment results

The main body of results and the main purpose of this study is to look at the impact assessment results for the different fuel types. The impact assessment calculations are the aggregation of all processes involved from the point of extraction leading to the refinery gate. The fuel types are separated by their usefulness and organized from highest emissions per MJ to lowest. The measure of the CO2-eq emissions is grams per MJ. The chart below summarizes the main CO2 data while exploring the range between the highest polluting refineries and lowest polluting refineries.

The blue bars represent the weighted average impact results for the entire UK. That is to say, the blue bars are representative of an average UK emission for the selected fuel. The range is shown as well to emphasize where the minimum and maximum values differ.

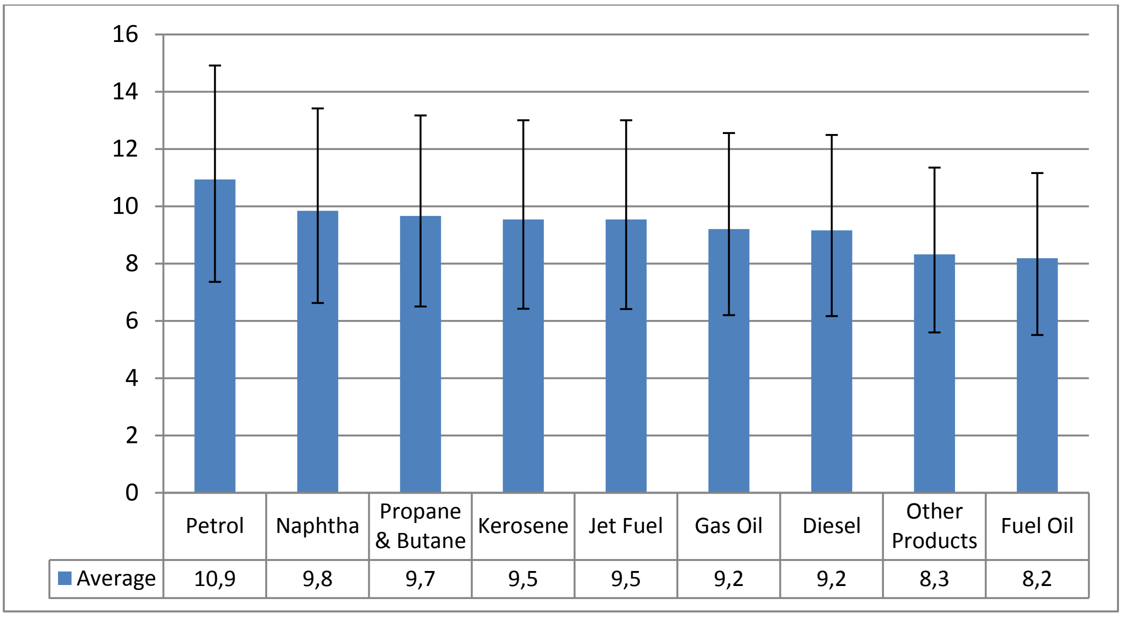


Figure 25 - g CO2-eq range and average per MJ by fuel type

Petrol has the highest value of emissions per MJ produced at 10.9 g per MJ on average in the UK. Using economic partitioning on the data makes a big difference on how the emissions are made and petrol typically has the highest value among refineries thus it takes the highest share of emissions for most refineries. Petrol processing also has other chemicals involved in the treating phase that cause more emissions, such as the use of butadiene.

Interestingly, the figures for naphtha and propane and butane are higher. The reason for this is because Stanlow, the most polluting plant in the UK, produces 22% of all light distillates (naphtha and propane and butane) in the UK. Though this is not the highest proportion in the UK, Stanlow's emissions are so great that it affects the entire UK average for the light distillates.

The Other Products are a measure of non-fuel products like lubricants and bitumen. Presenting those values in per MJ context is a bit disingenuous as these products will not be used for fuels. However, these other products represent less than 3% of the physical products produced and even less a percentage of economic value for the UK economy. Thus these products are relatively insignificant.

While the emissions were economically partitioned, the trend that one would expect is that greater market price would have greater emissions does not necessarily hold true. Petrol does have the highest market price for fuels while fuel oil has the lowest but overall there is not a particular trend to suggest that market prices and emissions are deeply embedded with each other.

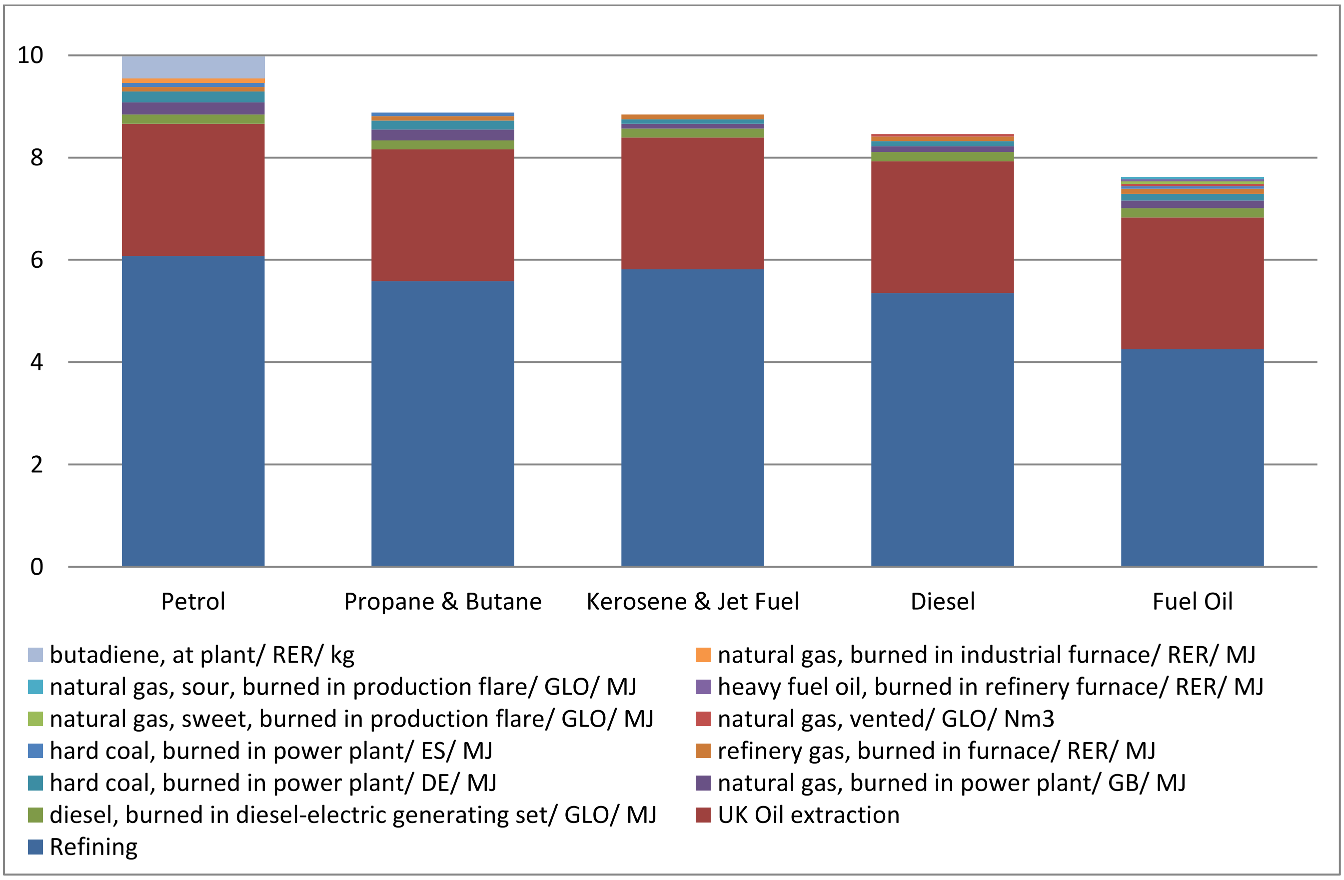


Figure 26 - g CO2-eq per MJ, by main processes, by fuel type

Dividing up the processes which create emissions can also be difficult. Unfortunately the resolution of the data did not allow for a differentiation of processes within the refinery however the box model amply allows for analysis. The following chart is a g CO2-eq by process. The two main contributors as seen on the chart on figure 26 are the blue and red portions. The red portion is the emissions from petroleum extraction while the blue portion is the direct emissions from refining.

The direct emissions from refining are the largest contributor to CO2-eq emissions while the extraction is the second highest and almost uniform for all fuel types. The petrol process is higher for added chemicals in the treatment phase, primarily butadiene, which adds an additional 0.42 g CO2-eq per unit petrol produced. The other background processes have negligible differences between fuel types. When the direct refinery emissions are calculated, there is almost a 33% difference between petrol and the lowest fuel, fuel oil. It should be noted that the g CO2-eq do not include emissions below a threshold of 0.5% total per fuel type and are lower than the absolute total.

The summary of these differences from the direct refinery process is in the chart below.

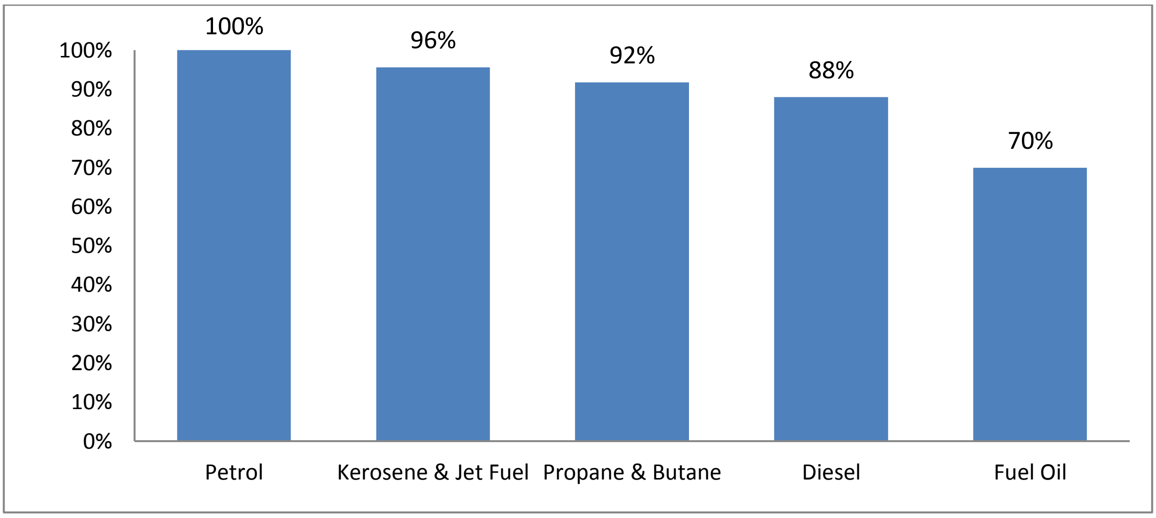


Figure 27 - Normalized CO2-eq emissions from the direct refinery process

Normalizing the refinery emissions allows for the emissions to be compared in an easier way. It is clear that the difference between fuel oil and petrol is quite stark as fuel oil has only70% of the direct refinery emissions of petrol. The division here is more closely related to fuel price with the exception of propane and butane, which again is skewed due to the production at Stanlow.

Kerosene and jet fuel, an expensive product, now emerges as the second greatest contributor to global warming from the direct refining process. In contrast to that, diesel is surprisingly low compared to petrol in direct process emissions as it is a major market product in the UK.

As diesel and petrol are the two main transportation fuels in the UK, further analysis is required among the other characterized impact categories for the impact analysis. As this study's main contribution is air emissions, other emission categories have been somewhat ignored.

The contribution analysis is an examination of normalized differences between diesel and petrol. The first takeaway from this chart is that in every category, petrol emissions are higher. Petrol is denoted in blue and diesel is denoted in red.

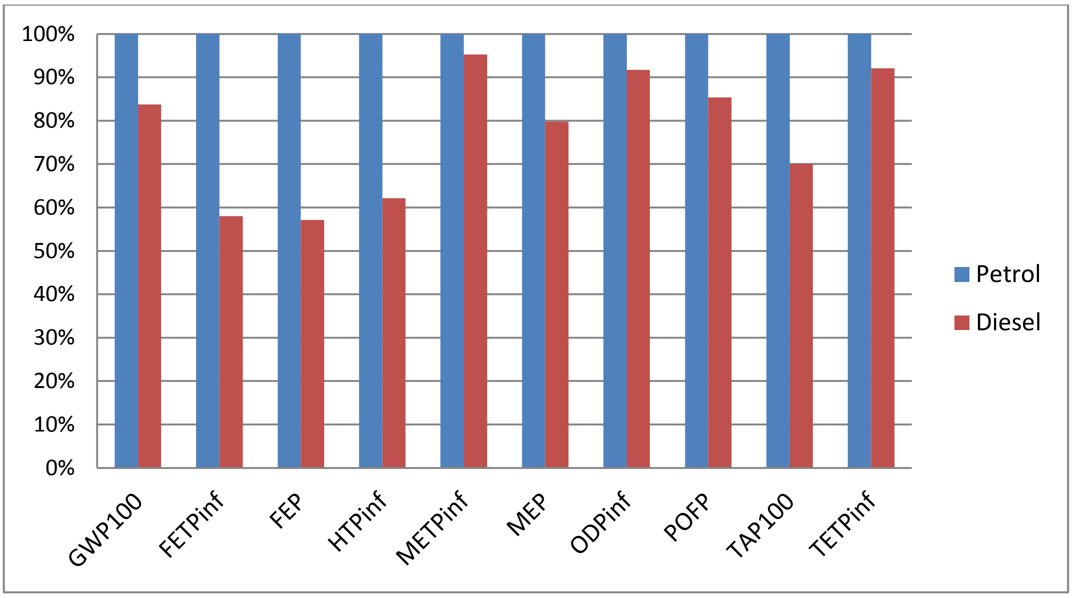


Figure 28 - Normalized refinery emissions between petrol and diesel, per MJ net fuel output

The GWP (CO2-eq) was already discussed in detail but the other categories worth noting are the ones with the greatest emissions differences between petrol and diesel. The freshwater ecotoxicology (FETPinf) emissions for diesel are approximately 58% of the same emissions for petrol which comes from the greater disposal of solid wastes from the background system for petrol. Higher rates of freshwater eutrophication (FEP) also are affected by the greater waste disposals in the background system.

The human toxicity potential (HTPinf) for diesel is approximately 61% of petrol. This is mostly due to the greater process emissions of arsenic in the direct refining of petrol. The marine eutrophication (MEP) is 80% of petrol for diesel, and that is again from greater direct refinery process emissions of nitrogen oxides for petrol. The terrestrial acidification (TAP100) is also higher for petrol than diesel due to higher direct refinery process emissions of sulfur dioxides than diesel.

Individual analysis is an excellent marker for each fuel but it is important to scale the results to be representative of the entire UK so that policy makers have a more relevant understanding for the entire refining industry. The following chart uses the emissions from the study to characterize each emission as a quantity of the UK petroleum cycle from ground to gate.

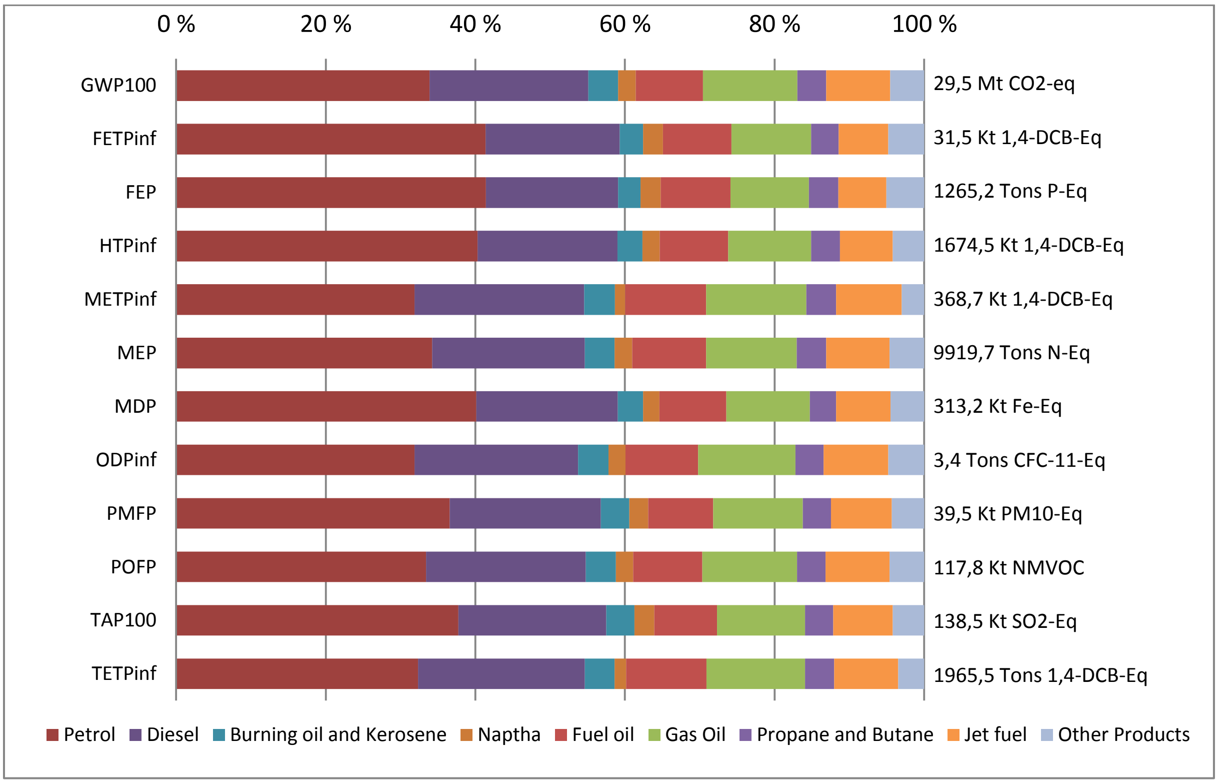


Figure 29 - Characterized emissions by fuel type, UK scaled total, 2009

The bar charts organize each characterized emission by fuel type as a percentage of total UK emissions from ground to gate process. On the right is the unit of measurement and the UK total for the ground to gate petroleum system and on the left is the impact category.

The first thing to take from the graph is the leading role that petrol production takes in emissions production scaling up. Petrol production was the highest emitter per MJ emissions for all impact categories and is also the highest gross emitter for the entire UK. Without a doubt, petrol production is the most damaging for the UK petroleum processing industry. There is no one single category where any other fuel has a higher gross impact in the UK than petrol.

Diesel is the second highest emitter for most impact categories but is a much lower emitter considering how much diesel fuel is actually produced. Petrol production is approximately 25% higher than diesel production but petrol production emissions are on average 40% higher. The production of diesel is more environmentally benign than that of petrol.

Jet fuel and fuel oil have approximately the same gross emissions while burning oil is not far behind. This is largely due to jet fuel having a higher market price than the other fuels even though physical production is lower.

Interestingly, looking at the entire chart is that the light distillate production (naphtha and butane and propane) which had such a high figure of CO2-eq per MJ produced is actually very insignificant on the total scale of the UK petroleum production. This is essentially because light distillate products are neither produced in significant quantities nor are very highly priced in the market.

The total CO2 from the process chain 29,5 Mt and the direct emissions of CO2 from the DECC for the entire economy is 16,6 Mt CO2 for the year 2009. By encompassing the entire process chain, the study realizes an additional 12,9 Mt CO2 previously unaccounted for.

While the CO2 increase is significant, of even more significance is the mapping of many more characterized emissions. The only previous scaled system for the entire UK was for CO2 emissions from the DECC. Now there are emissions accounted for 20 impact categories. This is a significant upgrade on the previously available data.

Lifecycle analysis scenario results

The impact assessment results offer a glimpse into the current petroleum production emissions of the UK. The results allow for greater resolution than what is currently available and greater resolution between the types of fuel consumed.

The main scenario analysis performed for this study is a comparison of current technologies. The information that is available on specific refinery processes may be unavailable but the information on some plant characteristics is. There are two refineries analyzed for scenario analysis: Fawley and Coryton. The Fawley refinery utilizes a CHP plant that makes the plant more efficient while the Coryton refinery uses a 779MW gas power plant as its main energy source. The two refineries are best suited for scenario analysis because the plants have similar output mix and the data available on each plant is of high quality.

The scenario analysis will offer some resolution on technology choices in the UK but first it is important to understand the emissions from each refinery as a sum total for the UK and the total production of each refinery. The following chart on figure 30 shows the reported output of all refineries in the UK.

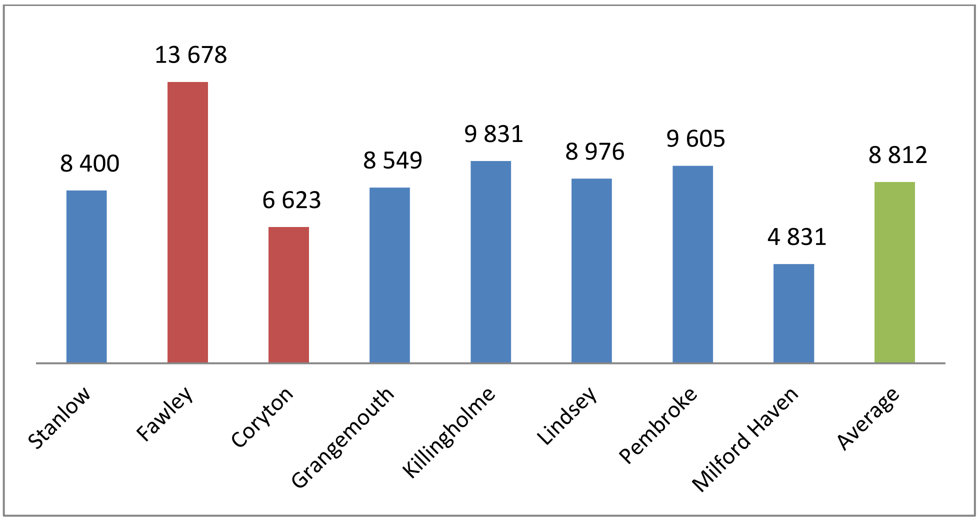


Figure 30 - Reported output (Kt) by refinery, UK, 2009

The biggest producing refinery is by far Fawley, at more than 13 million tons of product produced. The Coryton refinery is the second lowest producing refinery in the UK at less than half of Fawley. This low level of production is because the Coryton plant was not running at full production in 2009 due to maintenance and installation of new infrastructure and was only operating at 67% capacity (Petroplus International, 2010). Output mix as a percentage of total production was relatively similar for Coryton and Fawley refineries. These figures are the reported figures for output and not the results of the scenario analysis.

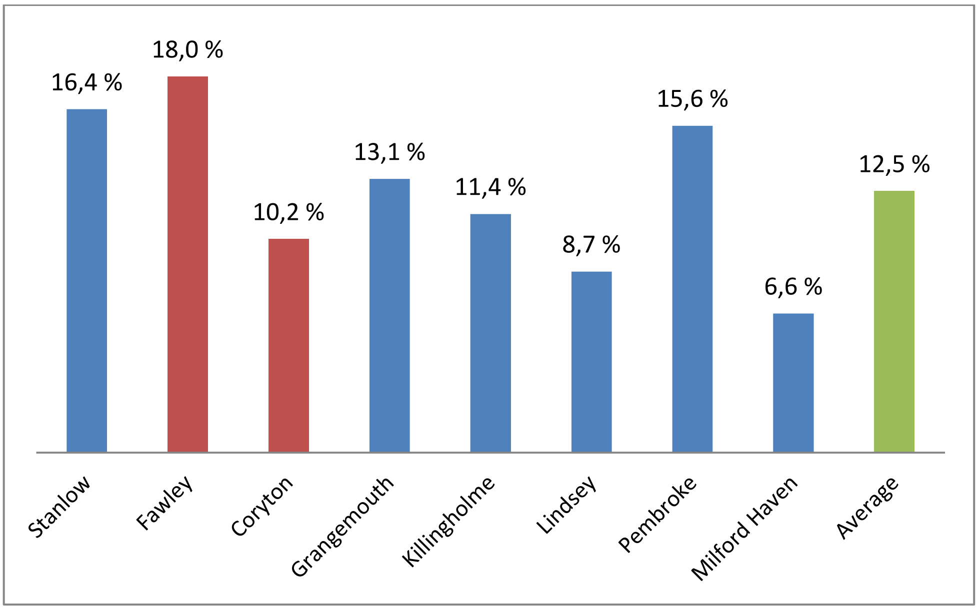
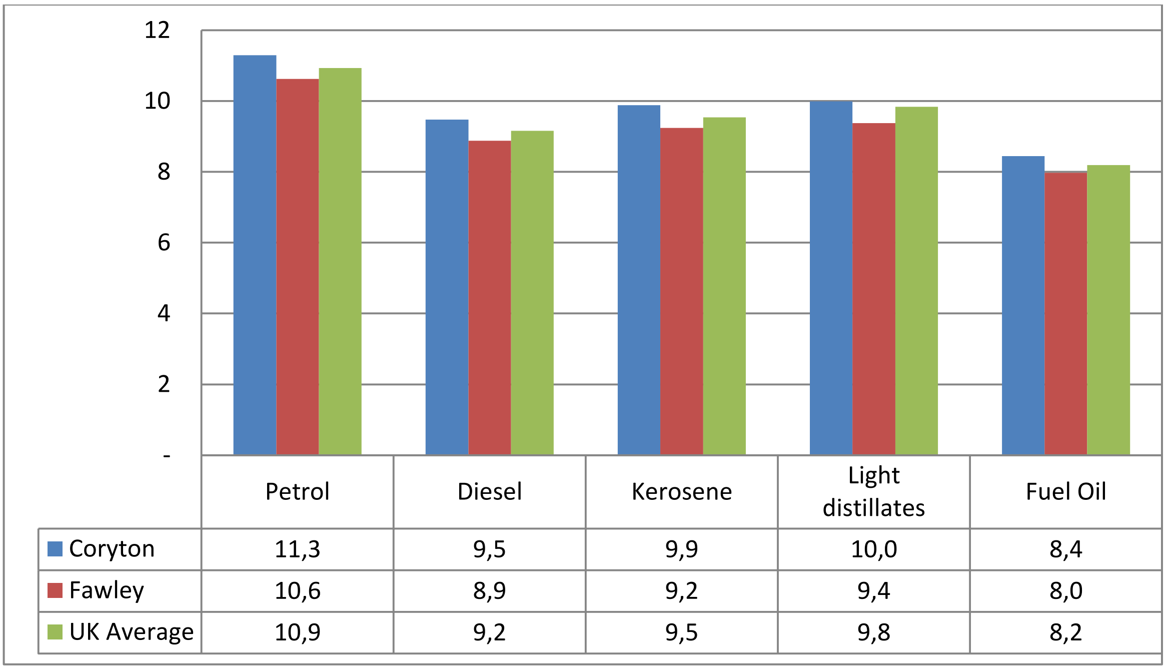


Figure 31 - CO2-eq share of total refining industry direct emissions, by refinery, 2009

It terms of gross total CO2-eq emissions, Fawley has the highest emissions in the entire country. This is mostly due to the fact that Fawley is the greatest producer of petroleum products. Coryton is responsible for 10% of emissions despite the fact that it is the second lowest producer of petroleum products at just over 9% of the UK total. This implies that Coryton is not as environmentally efficient as Fawley is. These preliminary results present the information that Fawley produces more CO2-eq emissions in terms of gross production but that Coryton is a greater producer of emissions in terms of per unit produced. The impact assessment results will show, with greater resolution on fuel outputs, the differences from these reported emissions.

The impact assessment follows the same pattern of presentation from the main study. The impact assessment results are broken down by the fuel types. The first chart is the g CO2-eq by fuel by plant.



	Petrol	Diesel	Kerosene	Light distillates	Fuel Oil
🟦 Coryton	11,3	9,5	9,9	10,0	8,4
🟥 Fawley	10,6	8,9	9,2	9,4	8,0
🟩 UK Average	10,9	9,2	9,5	9,8	8,2

Figure 32 - g CO2-eq per MJ net fuel output by scenario refinery

Petrol is again the highest producer of emissions on a per MJ basis. This is not a surprise. The second highest emitter per MJ is the light distillates followed by kerosene, diesel and finally fuel oil with the least emissions per unit.

A pattern that repeats itself throughout is that Coryton has the highest emissions per unit, above the UK average in every instance by between 0.15 and 0.42 grams CO2 per MJ for the different fuel types. Coryton also produces between 0.47 and 0.68 g CO2 per MJ more than Fawley over the different fuel types. This is a significant difference and shows that the CHP technology that Fawley is using is significantly reducing refinery emissions. One caveat to these results is the possibility that if Coryton were running closer to full capacity that this difference may be mitigated due to increased efficiency.

The scenario analysis as a whole also showed the same patterns in ranking the order of CO2-eq producing fuels as the main study with petrol, light distillates, kerosene, diesel and fuel oil being ranked in the same order. This suggests that these fuels could possibly be ranked in this order at almost all refineries. If the UK refining infrastructure was all configured in the same way as the Coryton refinery, emissions would be significantly higher while the converse would be true if all plants used CHP like Fawley.

Impact assessment is not only concerned with CO2 emissions however. The scenario analysis also brings to light the trade-offs that are made when utilizing CHP versus not using it. The differences among multiple midpoint characterized impacts are shown below for petrol production by Fawley, Coryton and the UK average and normalized to make comparison easier.

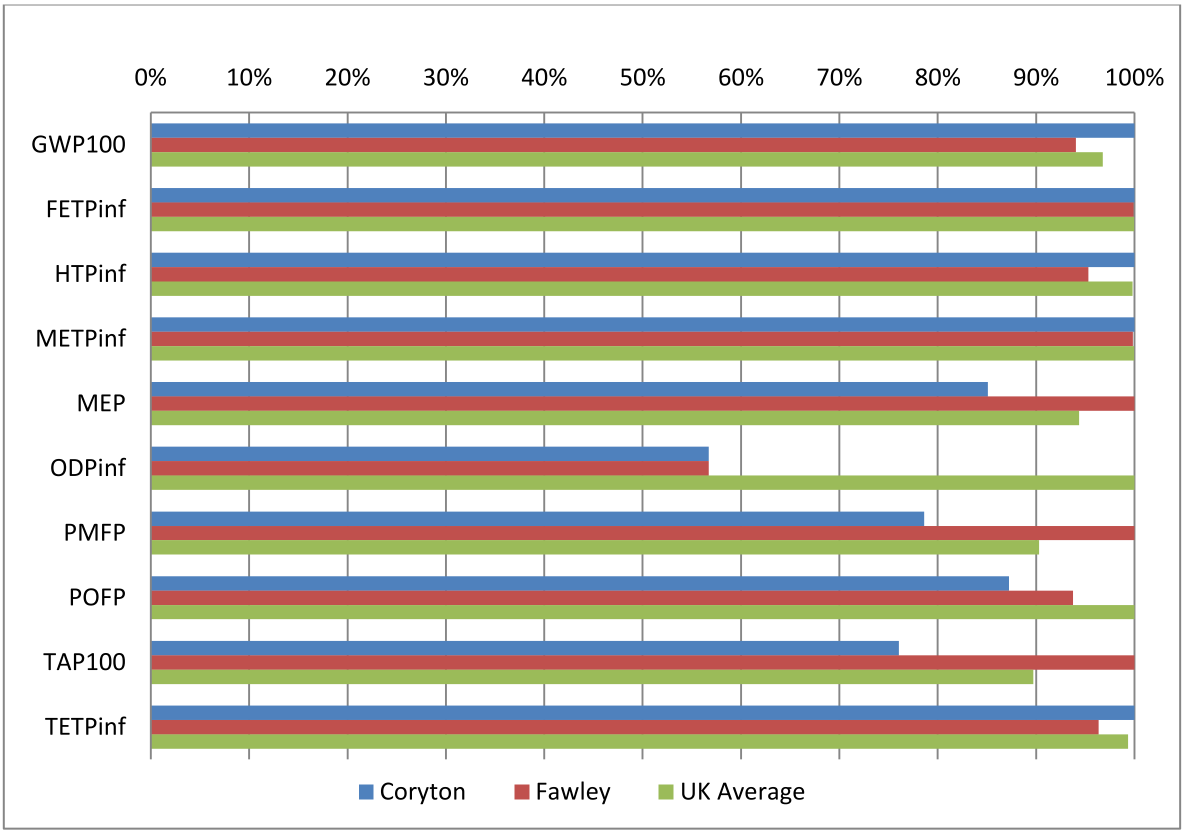


Figure 33 - Normalized values of impacts for Petrol refining, by scenario refinery

The trade-offs for using a CHP plant become more apparent here than by just analyzing CO2 emissions. The Fawley plant, while 6% lower than Coryton on CO2 emissions, is the leader in marine eutrophication (MEP), particulate matter formation (PMFP), and terrestrial acidification (TAP100) among the scenarios. The direct emissions are higher for MEP due to greater nitrogen oxides released in the Fawley plant. The PMFP and TAP100 are higher at Fawley because greater levels of sulfur dioxide are released in the direct refinery process. The Fawley plant releases more nitrogen oxides and sulfur dioxides as a result of their technology configuration.

Coryton is the highest among global warming potential (GWP) and terrestrial ecotoxicity (TETPinf). The GWP is higher because of higher direct process emissions. This is likely from greater direct energy inputs per unit output. The TETPinf is higher due to direct process emissions of phosphorus and bromine, which are slightly higher than the UK average.

The effect of having a CHP plant or a gas power plant makes no difference for FETPinf and METPinf. Curiously, both plants have a lower emissions impact for petrol than the UK average on ODPinf and POFP.

The results of the impact analyses are known. The next step was is to compare the results with those in the field.

Benchmarking

The results of the study are more meaningful when compared to the results of other studies or other analyses. The purpose of benchmarking is to give context to the obtained impact assessment results and to discover how the results validate or change the expected outcome.

The main body of information available to compare with comes from the EcoInvent database. The EcoInvent database is an aggregation of all European refining emissions and not specific to the UK. The first chart compares the differences between EcoInvent and the impact assessment results of this study in terms of CO2-eq by fuel type. The units given are g CO2-eq per MJ of fuel output. The EcoInvent data and this study share the same system boundaries of ground to gate.

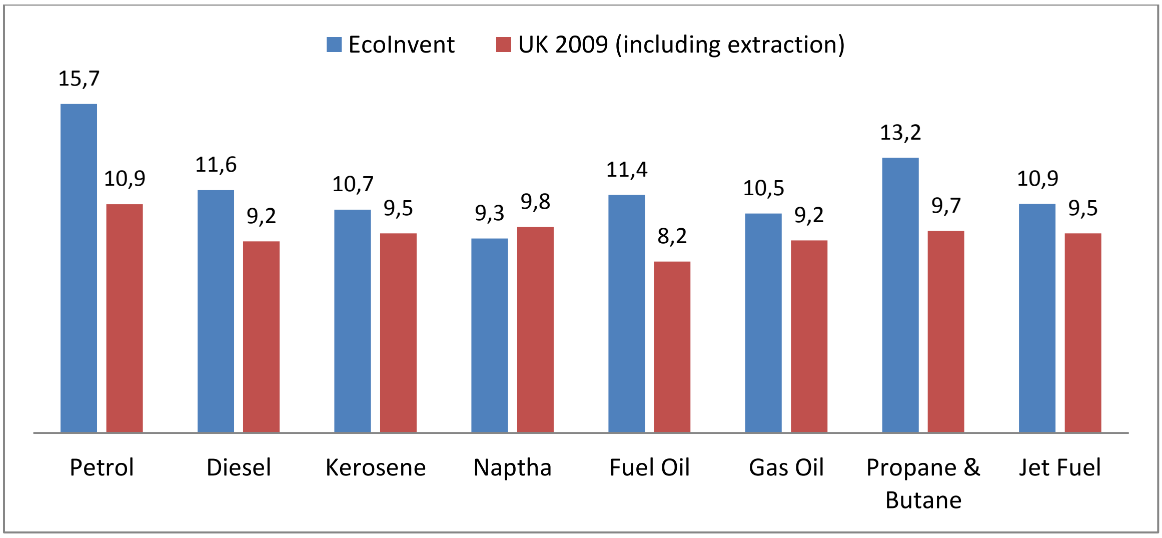


Figure 34 - g CO2-eq per MJ net fuel output between EcoInvent and study

The Ecoinvent data shows a much higher emission per MJ fuel produced for every fuel type except for naphtha. The skewing of the naphtha emissions from one refinery was previously discussed in the initial analysis. The other fuels are all higher and this could be for a number of reasons however the most sensible is that the use of European aggregated information does not take into account the differences in efficiency, technology, configuration or anything else.

Additionally, the EcoInvent data available comes from the year 2003, which means that the changes that have taken place over the period of the study and the EcoInvent data may not be accounted for in any way (Frischknecht, 2007). Besides the data itself, what these results imply is that the UK refining industry is more environmentally efficient than the European average.

The next chart shows the scale of these differences by normalizing the CO2-eq output per MJ.

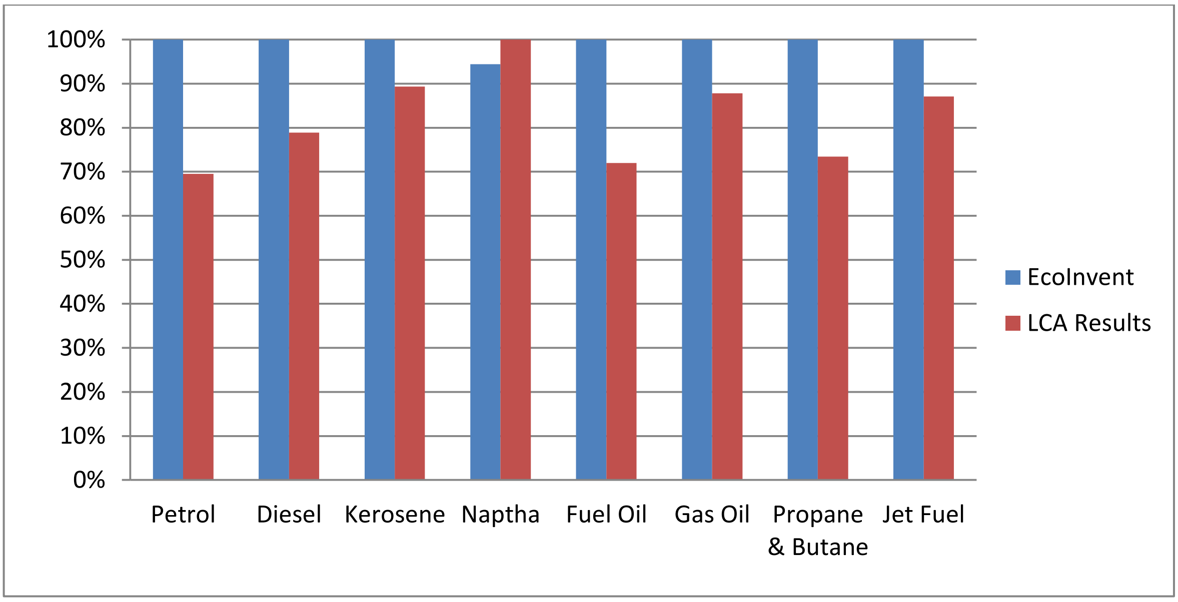


Figure 35 - Normalized CO2-eq per MJ net fuel output, EcoInvent and study

Petrol production produces just 70% of the average CO2-eq emissions from EcoInvent European average data while diesel is 79%. With the exception of naphtha production, which is higher for the study, the UK industry produces between 70% and 90% of the emissions per MJ fuel refined from the European average given by EcoInvent. These are substantially lower figures.

The next comparative data shown in figure 36 came from the DECC. The DECC CO2-eq figures only used the direct process emissions and not the ground to gate emissions which the study considered. As such, the study has higher emissions in every category because it considers the emissions upstream as well.

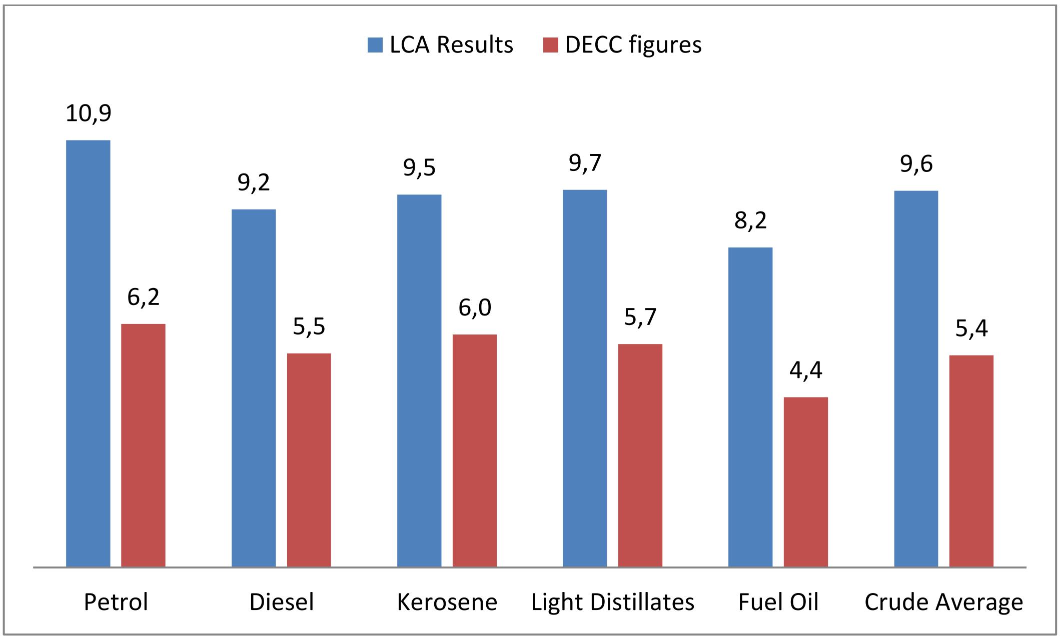


Figure 36 - g CO2-eq per MJ net fuel output, study and DECC

By looking at the entire process chain, the study succeeds offering a more complete picture of the CO2 emissions by including the process chain as well as the background processes such as refinery infrastructure that ultimately have an effect on the emissions.

The main difference in the results from using the DECC direct emissions versus using the results of the study is the ordering of greatest emitting fuels. The DECC ranking has petrol highest per MJ followed by kerosene, light distillates, diesel and fuel oil. The study has an order of petrol as the most polluting followed by light distillates, kerosene, diesel and fuel oil. Essentially the places of kerosene and light distillates have switched when doing a full process LCA.

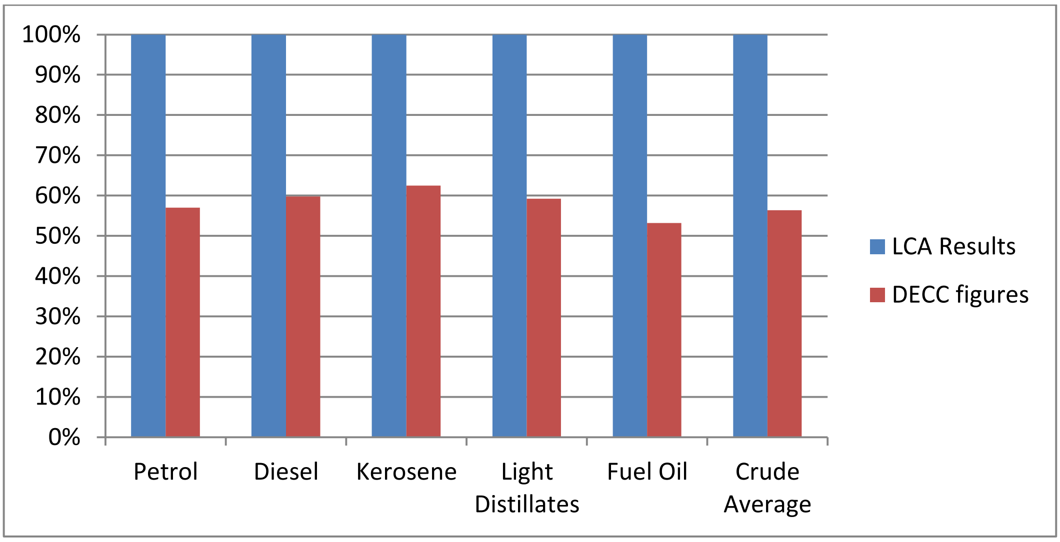
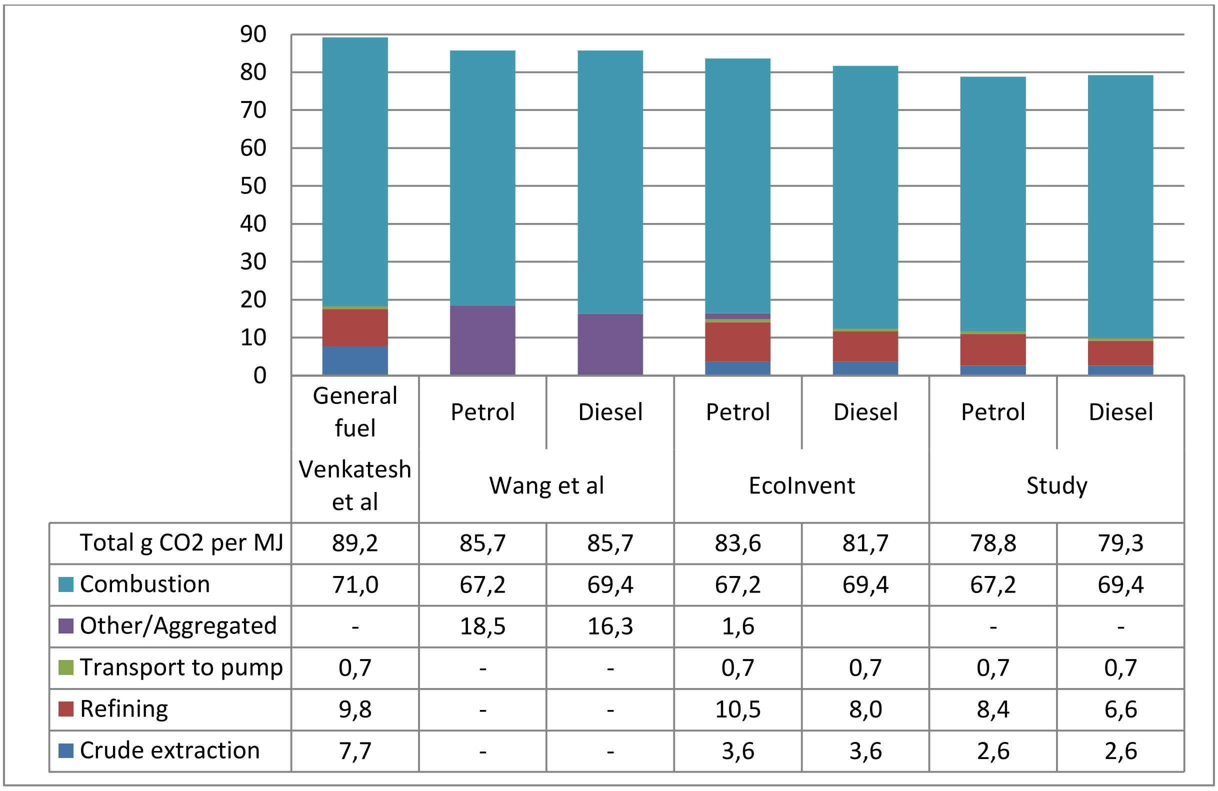


Figure 37 - Normalized CO2-eq per MJ net fuel output, study and DECC

In terms of actual gross emissions differences, adding a complete system varies the emissions substantially. The differences can be more easily seen in the normalized bar chart in figure 37.

When accounting for only the direct emissions, between 38% and 45% of the total emissions are being neglected. This offers a substantially greater picture for decision makers to be guided with. The biggest change in emissions comes from fuel oil, which nearly doubled when accounting for the entire system. Even petrol emissions were 72% higher than without the full system accounted for.

Finally, the last model for comparison is the EcoInvent data from the refinery usage, as was described previously. The system boundary for the EcoInvent data was extraction to refinery gate. The benchmarking of emissions is also relevant from the case studies discussed. The Wang et al and Venkatesh et al studies have results below.



	Venkatesh et al	Wang et al		EcoInvent		Study	
	General fuel	Petrol	Diesel	Petrol	Diesel	Petrol	Diesel
Total g CO2 per MJ	89,2	85,7	85,7	83,6	81,7	78,8	79,3
■ Combustion	71,0	67,2	69,4	67,2	69,4	67,2	69,4
■ Other/Aggregated	-	18,5	16,3	1,6		-	-
■ Transport to pump	0,7	-	-	0,7	0,7	0,7	0,7
■ Refining	9,8	-	-	10,5	8,0	8,4	6,6
■ Crude extraction	7,7	-	-	3,6	3,6	2,6	2,6

Figure 38 - CO2 emissions comparison between studies

The value of the y-axis is a measure of grams CO2-eq and that is broken down between each process from extraction to final combustion. The Other/Aggregated category is used to place emissions in EcoInvent that are not clearly defined by process and to show the aggregated emissions of the Wang study together with the other studies. Further, only the results of two fuels were shown as they are the most common energy fuel types used.

The study and the EcoInvent data require more information and an expansion of the system boundaries. To do this, the figure from the Venkatesh study for the transportation from refinery gate to petrol pump is used even though it may not be entirely accurate of the UK/Europe situation. The transport to pump is considered such a small value that it would have made the overall results nearly the same. Additionally, information on combustion is necessary to add a full well-to-wheel analysis. For the combustion emissions, simple combustion information from MIT Energy was added to supplement the Wang, EcoInvent and Study emissions to create a full comparison over all studies (Supple, 2007).

The greatest emitting refineries come from the US while the UK refineries are the least polluting along the process chain. The results are not particularly surprising as the differing methodologies and different geographical boundaries are taken into account.

Discussion

Completed objectives

The purpose of the study first and foremost was to find greater resolution for the petroleum process chain and the emissions coming from it. The study was a success in that greater information is now available for decision makers if necessary. The completion of all objectives for the study depended upon a series of data organization and compilation tasks. Successful completion also depended on following a particular order so that the next steps built upon previous steps. The first main objective was to compile data.

The compilation of emissions data was successful and required very little modifications. Tying the emissions data to production data required that each plant had information for both. The emissions data was relatively simple to find, coming from the UK NAEI. The production data required some effort and ultimately some estimations.

The main production data available came in the form of product mixes. Each refinery had a fixed mix of output per unit crude input that was dependent on the individual refinery configurations. Utilizing this product mix became important when it was clear that the refineries do not report their output in terms of products and very rarely report their gross output as a mixture of all products. The main concern for determining the production figures comes from the problem of data resolution. The process of output allocation addressed these concerns.

The successful estimation of production figures was a necessary requirement under the box refinery model used in this study. The partitioning of processes could not occur under the box refinery model so partitioning emissions on output was required to have meaningful results. The first step in the LCI involved allocating the different emissions to different outputs. As the box refinery model had shortcomings in the resolution of the processes, economic allocation on the output was required. To undertake economic allocation, the price of each commodity was needed. The ex-refinery price is the best price to use for refinery output. The ex-refinery price is the price that a product is sold for at the gate of the refinery. As this study only pertains to the refinery processes and upstream processes and not downstream processes, the ex-refinery price was suitable.

The ex-refinery price in Europe is protected trade information and unfortunately difficult to get a hold of. The only data available from the DECC pertains to consumer prices that are not of detailed resolution to be of any use for this case study. The price data instead came from OPEC and was based on Rotterdam ex-refinery pricing. Although using Rotterdam ex-refinery pricing is not ideal, it is the main pricing module for all refined fuels in Europe. With prices in hand, the economic allocation was done. Emissions were allocated by fuel type in each refinery as a measure of total economic output. The allocated emissions were then summated by fuel type from each refinery to the entire UK refining sector. The outcome was total emissions organized fuel type. This satisfies the study objective to economically allocate emissions information by fuel type.

Only one refinery reported no product mix while four refineries did not reveal total production. Luckily, the one refinery that did not report product mix did report total production meaning that the remaining output mix could be appropriated to the remaining four refineries as estimations. The estimated figures were inputted into each plant and emissions per unit calculated from the estimations. The result was a total picture of production and emissions by each plant, which is something that has not been publicly compiled for the year 2009. The DECC does have privately compiled production figures by each plant but refused to release them for this study.

The next step was to compile total UK production and emissions information. This was a very simple step and achieved by way of the DECC. The DECC had figures for production for the total UK refining industry and CO2 emissions for the entire UK refining industry. This DECC data was important in comparing the summation of all refinery production to the estimated refinery output. The total estimated refinery output from the study and total UK output from DECC were the same. This was a validation the estimations.

The emissions information for CO2 was also compared with the NAEI data to ensure that both sources matched. The NAEI and DECC data did match and thus the direct process refinery CO2 emissions were validated once more. The validation made it possible to continue with the construction of multiple LCIs.

To place the total UK data into an LCI requires additional maneuvering of the data. The LCIs should each share the same functional unit so as to offer a measure of comparability. The decision to use megajoules as the functional unit comes from the use of the products. Megajoules are the standard bearer of energy measurement for fuels therefore this functional unit was chosen.

To determine the MJ value of fuels in the UK, DECC average calorific values were used to convert the fuel output into MJ. The total emissions by each fuel was divided by total MJ value for each fuel type to arrive at a per MJ value of direct emissions from petroleum refining. The same process was repeated with the emissions and production data from Fawley and Coryton for the scenario analyses. The completed objective was to find average emissions per MJ per fuel type.

The average emissions were then inputted into LCI templates for each fuel type reported. The same input of data was done for the scenarios as well. The existing data was supplemented with background and stressor data from EcoInvent while extraction data came from the previous NTNU study. All the data was inputted into the foreground, background and stressor matrices. The completed objective was to organize and create LCIs for the different fuel types and scenarios. In total, eight LCIs were constructed for the main study and an additional 10 LCIs for the scenario analyses.

The next step was the impact assessment calculations. Using the NTNU ARDA software as a front end mechanism for calculations, 18 separate impact assessments were processed. The impact assessment also included structural path analyses for all major impact categories to a 15th tier in the process chain for further analysis. The compilation of these results into a separate data table for further analysis followed. The impact assessments calculations completed the objective to find all environmental impacts along the petroleum process chain.

The results for individual fuel types are excellent for comparing impacts between fuels but scaling all the data to reflect the total UK emissions is good for comparing with the totals from DECC for direct process emissions. The impact assessment results were scaled up for all UK refinery production and compared with the direct process emissions to see how much information was ultimately missing. The objective to scale up emissions was completed successfully.

Finally, the last step of the analysis process was to compare quantitatively with results of other studies of a similar nature. The EcoInvent data was the basis for comparison quantitatively. The results from the study were all within the same order of magnitude of the EcoInvent data, which confirms that the study, at the very least, is within the same range. The benchmarking process objective was successfully completed.

The main objectives of the project were to analyze the potential environmental impacts of the refining industry in the UK. The goal was achieved. A summary table of the main impact assessment results can be found below in figure 39.

IMPACT CATEGORY	Petrol	Diesel	Kerosene	Naphtha	Fuel Oil	Gas Oil	Propane & Butane	Jet Fuel	UNIT
ALOP	2,782E-05	1,270E-05	1,150E-05	2,045E-05	1,498E-05	1,275E-05	1,834E-05	1,149E-05	*m2a*
GWP100	1,093E-02	9,157E-03	9,540E-03	9,842E-03	8,189E-03	9,207E-03	9,661E-03	9,537E-03	*kg CO2-Eq*
FDP	2,370E-03	1,530E-03	1,475E-03	1,593E-03	1,614E-03	1,537E-03	1,542E-03	1,475E-03	*kg oil-Eq*
FETPinf	1,429E-05	8,286E-06	7,908E-06	1,202E-05	8,912E-06	8,312E-06	9,935E-06	7,906E-06	*kg 1,4-DCB-Eq*
FEP	5,739E-07	3,279E-07	3,069E-07	4,848E-07	3,650E-07	3,289E-07	4,206E-07	3,068E-07	*kg P-Eq*
HTPinf	7,390E-04	4,594E-04	4,494E-04	5,586E-04	4,719E-04	4,609E-04	5,424E-04	4,492E-04	*kg 1,4-DCB-Eq*
IRP_HE	4,846E-04	2,761E-04	2,491E-04	4,468E-04	3,289E-04	2,772E-04	3,982E-04	2,490E-04	*kg U235-Eq*
METPinf	1,287E-04	1,225E-04	1,222E-04	7,191E-05	1,231E-04	1,226E-04	1,243E-04	1,222E-04	*kg 1,4-DCB-Eq*
MEP	3,719E-06	2,966E-06	3,178E-06	3,413E-06	3,016E-06	2,978E-06	3,322E-06	3,177E-06	*kg N-Eq*
MDP	1,377E-04	8,679E-05	8,614E-05	9,820E-05	8,608E-05	8,676E-05	9,412E-05	8,613E-05	*kg Fe-Eq*
NLTP	3,037E-05	3,023E-05	3,018E-05	3,020E-05	3,032E-05	3,024E-05	3,020E-05	3,018E-05	*m2*
ODPinf	1,192E-09	1,093E-09	1,119E-09	1,111E-09	1,021E-09	1,099E-09	1,092E-09	1,119E-09	*kg CFC-11-Eq*
PMFP	1,582E-05	1,168E-05	1,212E-05	1,455E-05	1,055E-05	1,174E-05	1,264E-05	1,212E-05	*kg PM10-Eq*
POFP	4,313E-05	3,682E-05	3,807E-05	3,928E-05	3,365E-05	3,698E-05	3,812E-05	3,806E-05	*kg NMVOC*
TAP100	5,727E-05	4,012E-05	4,181E-05	5,321E-05	3,590E-05	4,035E-05	4,405E-05	4,179E-05	*kg SO2-Eq*
TETPinf	6,965E-07	6,415E-07	6,352E-07	4,347E-07	6,491E-07	6,434E-07	6,495E-07	6,350E-07	*kg 1,4-DCB-Eq*
ULOP	4,671E-05	4,049E-05	4,002E-05	4,096E-05	4,043E-05	4,054E-05	4,277E-05	4,001E-05	*m2a*
WDP	7,853E-06	4,623E-06	4,258E-06	7,105E-06	5,330E-06	4,642E-06	6,180E-06	4,256E-06	*m3*

Figure 39 - Summary of impact assessment calculations for main study, per MJ net fuel output

Implications

The prescient need for curbs on carbon dioxide emissions to mitigate climate change requires more information on how and where emissions occur within a process chain. The need is to focus attention on the biggest sources of emissions and work towards making more environmentally efficient refining processes.

The petroleum refining and processing industry is a major emitter of greenhouse gases and the results of this study can show how deciding which fuels to produce can create more or less emissions on a national level. The study has differing emissions figures from the numbers currently available from EcoInvent and from the direct process emissions of DECC. In a grand sense, the results add value in the form of greater resolution for understanding the environmental impacts of the petroleum process chain in the UK.

There are a few questions that this study brings to mind. The first query relates to why different fuel types have different results. There is no easy way to answer this but the main consideration comes from the allocation method and the differing energy contents of each fuel.

The economic allocation method was used. The emissions that were allocated on a plant level were then scaled up to reflect the entire UK economy. Petrol had the highest results simply because petrol had the highest market share of all refined fuels in the UK. As petrol remains a valuable product for UK refineries, it remains the driver of petroleum production and processing. The results reflect the importance of petrol as there is greater emissions intensity associated the product. In a more practical sense, petrol also goes through the most processes to become a finished product. This is not reflected explicitly in the box refinery model, but from the information available on refining theory and the results of the study, it is an agreeable result.

Using market price is a measure of what drives production in all industries and helps to separate the less important products. This separation of emissions by price also reflects that certain products are more important to refiners. In the context of the study, the more economically important fuels were in general the most polluting fuels. The exception to this is naphtha and other light distillate products as discussed previously, which brings up the point of individual refinery production having an effect on certain fuels.

Light distillate products had a high emissions load due to their larger scale production at higher emitting plants. These results make sense in the context of the British industry but would not necessarily be true in other jurisdictions. Because the individual processes and their associated emissions within the refinery are unknown, the results depend more upon which refinery produces the product than what processes occur. It may be that the reason the Stanlow plant has higher emissions is due to the production of one product over another, which skews all emissions upwards for all other products in the box refinery model.

However, as a representation of all products in the UK, the flaws from using the box refinery method will be smoothed out for the most part for products that are produced in large quantities. As the largest quantity products are the products that garner the most interest in this study, this smoothing over is imperative for the results to be valid. For lesser produced fuels, the skewing of certain refinery emissions is likely felt but ultimately not as important as getting the results right for petrol, diesel and the other major refinery products.

The EcoInvent information brings to light another interesting implication of this study with respect to how UK refineries are represented. The EcoInvent emissions figures for CO2-eq emissions were higher across the board except for naphtha. This is due to the fundamentally different scope that EcoInvent takes by analyzing for a European average.

The problem with the European average is that it may very well be representative of Europe but it does not effectively characterize the emissions situation of UK refining. This study offers new LCI and LCA information related to the specific UK outputs that is currently unavailable from EcoInvent. The differences from EcoInvent come from greater detail on the stressor matrix based upon what each refinery is emitting. Additionally, the European average for different refined fuels comes from a survey in the year 2000. EcoInvent makes no qualms about this and is entirely transparent in their inventories stating that the figure given is representative of just 5% of the European refining sector (Frischknecht, 2007). Given the meta-information from EcoInvent, it is somewhat unrealistic to consider the data from EcoInvent representative of the UK.

The results have shown UK emissions are lower than EcoInvent's European averages. The implication in this is that there is an assumption the EcoInvent information is not representative of the UK and thus requires the modification carried out in this study to be more representative. This is likely not a flaw in EcoInvent's model, just a reality within the scope of what the model represents. The findings in this study show a more environmentally efficient petroleum refining industry in the UK than what is shown in EcoInvent for the rest of Europe.

The DECC emissions also show a different total of CO2 emissions than what the study shows. This is due to the scope of the study extending outside of direct process emissions and into the upstream processes that relate to petroleum production. The DECC data is a year-by-year analysis of reported process emissions summated from all refineries. As such, the data reported from DECC does not include information on other processes like extraction or the infrastructure or anything else besides what happens within the direct refinery process.

Essentially, the study encompasses a greater share of the process chain for petroleum and the associated emissions. The purpose of the study was to expand the system boundaries so as to have a fuller body of knowledge of the process chain in the UK. The work that was done at NTNU on petroleum extraction in the UK was monumental to completing this study for the entire lifecycle chain from ground to gate. The implication is that with a greater depth of understanding, the decisions being made based on the emissions of particular fuels can now be made in a more informed manner. This is helpful for petroleum companies, government officials and environmental advocates as petroleum products should not be evaluated only on the merits of combustion emissions alone.

The scenario models also help to refine our understanding of the petroleum process chain to incorporate different technologies. The unfortunate aspect of the box refinery model is that processes are not separated clearly to understand where environmental efficiencies can be further embraced. However, by separating out the different refineries with the understanding that each refinery has different technologies to manage the same outputs, a clear picture on technology use can be seen.

The scenario models are summarized simply as two refineries which produce similar output mixes but with different configurations. The Fawley plant is the largest in terms of capacity and output in the UK and utilizes a CHP system to improve process efficiency while the Coryton plant still uses the more conventional gas powered process plant without CHP. The differences in emissions per unit output are not so large as to make a major difference on a small scale. Coryton produces just over 6% more emissions per unit petrol, for example.

The difference in emissions is small on a per unit basis but if the entire UK refining industry adapted to include CHP process plant, there could be reductions of direct process CO2 emissions by more than 5%. If all refineries were able to reduce their emissions by 5% by installing a CHP process plant, then meeting the European Fuel Quality Directive of 6% reduced emissions by 2020 would be simple.

There is a tradeoff from the use of CHP in that other emissions in some categories increase. Whether this is due simply to other configurations unrelated to the CHP plant at Fawley is not fully understood. The main implication, however, is that CO2 emissions can be reduced by utilizing CHP. This is due to decreased energy inputs from greater process efficiency and the weak assumption is that CHP can improve the CO2 performance of the UK refining sector.

The information presented in this study is meant to offer greater resolution than the information currently available from EcoInvent and the direct emissions information available for refineries in the UK. The purpose is to present lifecycle emissions information for the UK refining sector that was not currently available through any accessible means. The study is an integrated effort to bring the environmental picture of refining into full focus.

The value that this study adds to the field is that only direct emissions were known for the UK refining industry previously. The direct emissions are important but they are indicative of only part of the environmental impacts associated with petroleum production. Without fully acknowledging that there are emissions from other processes besides the direct combustion, decisions are being made without due process. For the refining industry in the UK, there is probably a desire to promote increased petrol consumption in the face of declining consumption and decreasing domestic petrol profits. As a countervailing point, the environmental protection organizations in the UK could desire that the current levels of petrol consumption decline even further because of the environmental harm being caused from the refining and use of petrol. Both parties have requisite environmental information from this study to promote one fuel over the other or promote one technology over the other. The implication is that this study gives more environmental impact information on the UK petroleum chain to the people who need it to make informed decisions.

The lifecycle emissions of a product that uses refined fuels in the operating phase can be affected by the differences in emissions from refining. If a motor vehicle that is using refined fuels from the heavily polluting Stanlow refinery versus using fuels sourced from the Lindsey refinery, where each unit of fuel produced is less than half as carbon intensive, the full lifecycle results can be huge. The following case study organized by Mercedes analyzes the full lifecycle of the of their C-Class automobiles (DaimlerChrysler AG, 2006). The results below show the full lifecycle emissions from vehicle production to end of life recycling. Interestingly, the fuel production is included.

Figure 4-3: Lifecycle phases related to selected parameters

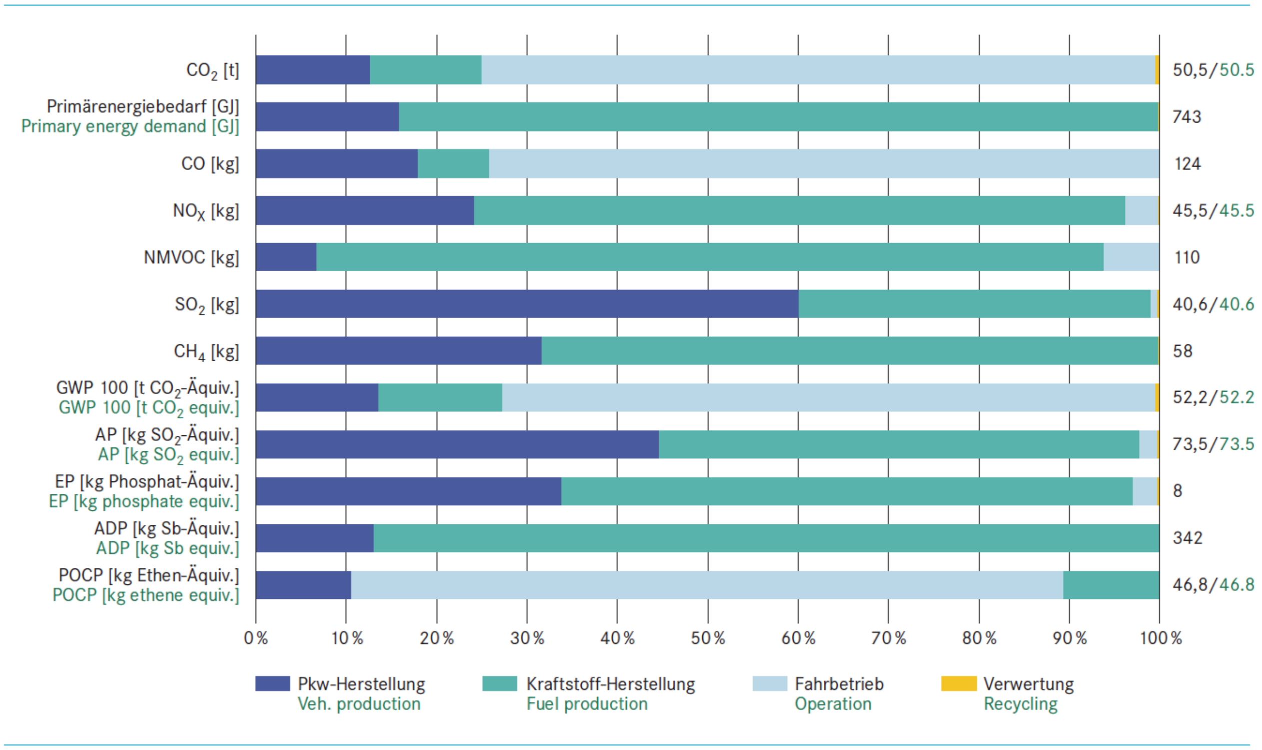


Figure 40 - Lifecycle analysis of the Mercedes C-Class

When looking at the CO2 emissions, which have thus far been one of the main criteria for this study, the fuel production makes up approximately 10% of the CO2 emissions for the lifecycle of the car. This is not an insignificant quantity and if it was possible to halve these production emissions by sourcing from a plant like Lindsey and not from a plant like Stanlow, the total lifecycle reductions in

CO2 from the car would equal 5%. The assumption that the fuel being used comes from a refinery that is very polluting but that may not be the case anyways.

The one takeaway from the Mercedes case study is that refinery emissions do make a substantial impact on the lifecycle emissions of individual products and must be considered a core part of reducing environmental impacts. The main impacts that the petroleum production has on the Mercedes C-Class is on acidification potential (approximately 55%), eutrophication potential (greater than 60%), and nearly 90% of abiotic depletion (ADP). These are substantial impacts to the environment that must not be ignored.

If petroleum processing industries were more environmentally responsible then a plethora of products which use petroleum would be as well. The implication of the Mercedes case study is that the environmental impacts of petroleum processing and extraction are felt further down the product chain. If refinery impacts can be reduced then the path towards a more sustainable energy system will be the result.

Results discussion

In the study “Uncertainty Analysis of Life Cycle Greenhouse Gas Emissions from Petroleum-based Fuels and Impacts on Low Carbon Policies” (Venkatesh, Jaramillo, Michael, & Matthews, 2011) by Venkatesh et al, a full process chain from extraction to combustion is characterized by the CO2 emissions. The system boundary for the study is a full well-to-wheel analysis. The method used in this case for determining refinery emissions came from the measuring energy inputs into the refinery and estimating the emissions as combustion occurs and depending on what the source of energy is. There is no process breakdown with respect to refining in the Venkatesh study but there are further breakdowns in processes along the chain until the combustion occurs.

The Venkatesh study does not measure direct refinery emissions nor does it breakdown the emissions by fuel type. However, the transport from refinery to tank is included and is offered as the basis for comparison among all fuels. The Venkatesh study utilizes data from EcoInvent for extraction information and US Energy Information Administration (EIA) data for the energy use at refineries. The geographical scope of the Venkatesh paper is the United States which offers some basis of comparison, but not based on geography. It also has a time period

In the Wang et al study “Allocation of Energy Use in Petroleum Refineries to Petroleum Products” took a look at the refinery model and the effects of allocation in a system with well-to-pump boundaries (Wang, Lee, & Molburg, 2003). The emissions are not disaggregated in any way as the method for organizing which emissions occurred where were based on energy inputs to the refinery processes and estimated emissions outputs from energy production. The system boundary of the Wang study is well-to-gate, the same as the base case.

The main method for determining refinery emissions in the Wang study was the same as the Venkatesh study. Wang et al used analysis of energy inputs to production coupled with refinery emissions data from a 1996 study. The data was allocated according to multiple criteria but what is of most interest is the analysis carried out after undergoing economic allocation. The Wang study had prices sourced from a 1999 US Energy Information Agency report with the results being characterized on a CO2 g per MJ fuel output. There is no disaggregation between processes of extraction or refining within the Wang study but total process chain CO2 emissions are known. The results from the economic allocation portion of the Wang study were representative of a similar system boundary to the Venkatesh study with the exception of combustion. The geographical boundaries for Wang study were within the United States and representative for the year 1999.

The results of multiple studies and the results of this study compare favourably but offer no direct comparison to the UK refining industry. As stated before, EcoInvent measures European averages and the Wang and Venkatesh studies are formed in the US. The results of this paper add new geographical region to refining industry information and assumes lower emissions than the European average from EcoInvent and the American averages from two thorough case studies.

The UK study also differs in methodology from the two US studies in that the direct refinery process emissions information is derived from overall plant emissions and not considered purely from energy inputs. The UK study conducted is considerably more inclusive and representative of the actual emissions versus what the Wang and Venkatesh studies put forth because they deal with actual emissions instead of estimates.

The method of using market price to allocate emissions can be considered problematic in that prices constantly fluctuate. Using historical prices and historical data means that the information given is not present day but rather a snapshot in time. It is a reasonable assumption to make that conditions have remained relatively the same given that the study base year is from 2009 and this paper was written in 2012.

The methodology used follows standard LCA protocol and mirrors the similar processes for EcoInvent. The major changes to the EcoInvent information were in the form of updated extraction information and updated direct refinery process information. The quality of the results for this study come from the data being newer and the information being allocated first at the refinery level so that refinery configuration showed a detailed difference between fuels produced. The allocation at the refinery level corrected for the watering down process that aggregating all emissions and outputs together before allocation. The refineries have very specific outputs and specific levels of emissions which mean that allocation at the refinery level creates far more accurate results.

The main finding of the scenario analysis is interesting in that a refining with a CHP plant had nearly 6% less CO2 emissions than one which operated a conventional gas powered plant. The European Fuel Quality Directive strives to reduce CO2 emissions in petroleum process refining by 6% by the year 2020. The technology to meet this reduction already exists and can be implemented rather easily. Policy makers could mandate that all refineries be required to install a CHP facility in order to reduce emissions by reducing energy use.

The best information available on the lifecycle impacts of the petroleum industry in the UK previously relied upon data that was not congruent to the reality of the UK situation. Other studies used proprietary data that was made up of data that is not from the UK. The UK impacts of petroleum processing throughout the process chain were not modeled in a coherent way nor were they linked between processes. This study is the most recent academic study pertaining to UK petroleum processing and as such fills a research void.

Areas for further research

The UK study is a strong beginning for analyzing impacts of the petroleum process chain but could be improved in a few measures. The inherent lack of data is always the most difficult part of conducting an LCA study in that data is often low quality, not organized, or not available. The typical approach is to create a patchwork of data and use educated and generally sophisticated estimates to fill in gaps of knowledge. The problem with poor data is that it can create inaccurate results.

While the results of this study are not at risk for being particularly inaccurate with respect to emissions from air, the other emissions information requires more detail. The NAIE data was very detailed for the refinery output for all emissions to air that were relevant to the impact assessment but the use of EcoInvent for the water emissions leaves more to be desired. The EcoInvent data for water emissions come from the European averages as the UK refiners do not publicly state emissions to water. The lack of detailed UK specific water emissions was a hindrance to the results of this study and as such the water emissions results were not heavily emphasized. Future additions of water emissions with better resolution would greatly enhance that aspect of the study.

The way that air emissions are reported from refiners is that there are no process level emissions. The amounts of emissions created by a vacuum distillation unit versus a catalytic cracker are not reported in the NAEI data that was used for this study. This lack of resolution led to the creation of the box model for refinery emissions. The box model and output allocation amply modeled emissions by fuel output but not by production process.

Previous studies looked at the energy inputs to each of the processes and estimated emissions from combustion of the energy outputs and not the actual emissions being produced from the refinery processing. A better way to help approximate emissions by fuel type could be a hybridization of the two system models: using energy inputs to each fuel and refinery emissions outputs to try and partition emissions towards a process within the refinery. This would involve some reconciling from the estimated emissions and the actual emissions by apportioning emissions on individual refinery processes but it could be conceivably done.

The box refinery model ignores this sort of energy input analysis and economic partitioning of emissions renders a hybridized model somewhat irrelevant as the study is concerned with what fuel is driving all production of the co-products. The hybridized model could provide a more detailed approach for both fuel outputs and the processes which utilize them but due to the constraints of time and the lack of process inputs available in the UK system, the box refinery model was considered the best model for the job.

The box refinery model relies heavily upon using the output from each refinery to partition emissions to each fuel type. The output information in this study was estimated for four refineries for approximately 50% of the total output of the entire refining industry. The hope is that the plant estimations do not affect the emissions by fuel type so greatly as to skew the results. The addition of actual output data for this model for all the missing refineries would greatly enhance the results at least in terms of precision. The information is available at the DECC but it is not publicly available data. The process of aggregating all data together thus becomes very important in providing an average emission figure.

The results of this study are a strong representation of averages for the entire UK industry but likely not a full representation of what to expect at each refinery, as the scenario analyses have shown. These results are representative on a macro-level for the UK but probably less than indicative for each refinery. This is an agreeable outcome given that the purpose of the study was to model the entire petroleum processing industry. The groundwork for future studies has been laid and the model can easily be modified for working on several refineries separately.

Conclusion

Policy makers can find value in the results from the study to aid in defining policies moving forward. For example, the scenarios noted that the reductions in CO2 emissions were quite substantial when utilizing CHP. A policy maker would thus be interested in ways to convert plants to utilize CHP technology if reducing CO2 was a policy goal. Another goal may be the continued promotion of diesel fuel over petrol for CO2 emissions concerns. The results of this study offer a climate change centric argument towards making the full shift from petrol to diesel. Policy makers could now have a basis besides combustion to make their decision on which fuel types should be promoted for transportation use.

The results show that the UK refining industry is typically more environmentally efficient than the average refinery in Europe according to EcoInvent data. This is a boon to UK producers who wish to tout the advantages of producing refined petroleum products in their country in the face of a declining market. Refiners in the UK on the whole would be very interested in these results because environmental awareness is higher than ever before in the consciousness of consumers and citizens alike. The industry should strive to continually improve emissions performance so this study also offers a base for benchmarking their improvements.

Academics and impact assessors also have a base to work with for the British petroleum process chain. As previous studies relating to the petroleum refining industry made use of European averages for extraction and refining, this study offers more information to academics to analyze and scrutinize.

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Appendix

I. Total product output in Kt, by refinery, 2009

Refinery	Total capacity	Reported output	Petrol	Diesel and gas oil	Kerosene / jet fuel	Fuel oil, bitumens, lubricants	Light gases and feedstocks	Other products (unclassified)	TOTAL
Stanlow	12 000	9 918	2 850	3 325	1 900	950	892	-	9 918
Fawley	16 000	13 162	3 856	3 994	1 515	2 066	1 040	689	13 160
Coryton	10 000	6 710	2 432	1 824	743	1 622	89	-	6 710
Grangemouth	10 000	8 313	1 914	2 784	1 131	1 305	658	522	8 313
Humber	11 500	9 301	2 997	4 121	749	937	123	375	9 301
Lindsey	10 500	8 574	2 293	2 751	1 192	1 376	962	-	8 574
Pembroke	10 500	9 605	2 381	4 862	1 112	864	-	341	9 559
Milford Haven	5 400	4 909	1 681	1 732	509	713	324	-	4 958
TOTALS	**86 500**	**70 494**	**20 404**	**25 393**	**8 852**	**9 832**	**4 087**	**1 926**	**70 494**

II. Product mix by refinery, as a percentage of total production, by market value

Refinery	Petrol	Diesel & Gas oil	Kerosene & Jet Fuel	Fuel oil, Bitumen, & Lubricants	Liquid Petroleum Gases and Feedstocks	Other products
Stanlow	29 %	34 %	19 %	10 %	9 %	0 %
Fawley	29 %	30 %	12 %	16 %	8 %	5 %
Coryton	36 %	27 %	11 %	24 %	1 %	0 %
Grangemouth	23 %	33 %	14 %	16 %	8 %	6 %
Humber	32 %	44 %	8 %	10 %	1 %	4 %
Lindsey	27 %	32 %	14 %	16 %	11 %	0 %
Pembroke	25 %	51 %	12 %	9 %	0 %	4 %
Milford Haven	34 %	35 %	10 %	15 %	7 %	0 %

III. UK average calorific values of fuels, 2009

	MJ per kg	
Petroleum:	Net	Gross
Crude oil (weighted average)	43,4	45,7
Petroleum products (weighted average)	43,8	46,1
Ethane	46,6	50,7
Butane and propane (LPG)	45,9	49,2
Light distillate feedstock for gasworks	45,4	47,8
Aviation spirit and wide cut gasoline	45,0	47,4
Aviation turbine fuel	43,9	46,2
Motor spirit	44,7	47,1
Burning oil	43,9	46,2
Gas/diesel oil	42,5	45,3
DERV	42,9	45,6
Fuel oil	40,7	43,3
Power station oil	40,7	43,3
Non-fuel products (notional value)	40,9	43,1

IV. Petrol foreground system

	Label (PRO_f):			y_f:	A_ff:	1	2
	FULL NAME	**PROCESS ID**	**UNIT**			**Final refined product**	**UK Oil extraction**
1	Final refined product	10001	MJ	1			
2	UK Oil extraction	10002	kg			**0,02306**	

V. Petrol background system

Background Process Name	***Foreground Process Name***	***(Matrix Row position)***		
Comment	***Comment***	***BACKGROUND PROCESS ID #***	***VALUE***	*Unit*
Methyl tert-butyl ether, at plant/RER U	End petroleum product	752	0,000557276	kg
Tap water, at user/RER U	End petroleum product	3386	0,000324284	kg
Calcium chloride, CaCl2, at plant/RER U	End petroleum product	462	3,45632E-07	kg
Hydrochloric acid, 30% in H2O, at plant/RER U	End petroleum product	494	1,89878E-06	kg
Iron sulphate, at plant/RER U	End petroleum product	1831	1,06674E-06	kg
Lime, hydrated, packed, at plant/CH U	End petroleum product	839	7,46722E-07	kg
Lubricating oil, at plant/RER U	End petroleum product	740	5,2911E-07	kg
Nitrogen, liquid, at plant/RER U	End petroleum product	530	1,75798E-05	kg
Soap, at plant/RER U	End petroleum product	2976	5,71761E-08	kg
Sodium hypochlorite, 15% in H2O, at plant/RER U	End petroleum product	581	1,06674E-06	kg
Sulphuric acid, liquid, at plant/RER U	End petroleum product	603	2,53892E-07	kg
Transport, lorry >16t, fleet average/RER U	End petroleum product	2807	1,50835E-05	tkm
Transport, freight, rail/RER U	End petroleum product	2887	9,04584E-05	tkm
Electricity, medium voltage, production UCTE, at grid/UCTE U	End petroleum product	984	0,001237429	kWh
Refinery gas, burned in furnace/MJ/RER U	End petroleum product	4004	0	MJ
Heavy fuel oil, burned in refinery furnace/MJ/RER U	End petroleum product	3423	0	MJ
Refinery gas, burned in flare/GLO U	End petroleum product	4016	0	MJ
Refinery/RER/I U	End petroleum product	3844	1,1027E-12	p
Ammonia, liquid, at regional storehouse/RER U	End petroleum product	444	4,28765E-08	kg
Naphtha, at regional storage/RER U	End petroleum product	2365	0,00085326	kg
Chlorine, liquid, production mix, at plant/RER U	End petroleum product	475	2,91916E-06	kg
Chemicals organic, at plant/GLO U	End petroleum product	673	4,0735E-06	kg

Propylene glycol, liquid, at plant/RER U	End petroleum product	780	4,40724E-07	kg
Molybdenum, at regional storage/RER U	End petroleum product	1856	1,75927E-09	kg
Nickel, 99.5%, at plant/GLO U	End petroleum product	1857	2,73675E-10	kg
Palladium, at regional storage/RER U	End petroleum product	1861	1,78002E-09	kg
Platinum, at regional storage/RER U	End petroleum product	1869	5,63557E-11	kg
Rhodium, at regional storage/RER U	End petroleum product	1889	5,63557E-11	kg
Zeolite, powder, at plant/RER S	End petroleum product	2958	3,93379E-07	kg
Zinc, primary, at regional storage/RER U	End petroleum product	1923	4,24294E-09	kg
Discharge, produced water, offshore/OCE U	UK Oil extraction	2474	1,197080292	kg
Chemicals inorganic, at plant/GLO U	UK Oil extraction	469	0,000055392	kg
Chemicals organic, at plant/GLO U	UK Oil extraction	673	0,000049289	kg
Transport, lorry >16t, fleet average/RER U	UK Oil extraction	2807	0,000010609	tkm
Transport, freight, rail/RER U	UK Oil extraction	2887	0,000062903	tkm
Diesel, at regional storage/RER U	UK Oil extraction	2343	0,0026804	kg
Heavy fuel oil, at regional storage/RER U	UK Oil extraction	2352	0,0021969	kg
Well for exploration and production, offshore/OCE/I U	UK Oil extraction	3857	4,69E-006	m
Platform, crude oil, offshore/OCE/I U	UK Oil extraction	3854	3,29E-011	p
Pipeline, crude oil, offshore/OCE/I U	UK Oil extraction	3852	3,33E-009	km

VI. Petrol stressor matrix

STRESSOR NAME	***FOREGROUND PROCESS NAME***	**(Matrix row)**	**(Value)**	***UNIT***
Comment	***Comment***	**STRESSOR ROW #**	**AMOUNT**	***Comment***
13-butadiene	Final refined product	1	1,11E-08	kg
Acenapthene	Final refined product	12	5,49E-11	kg
Ammonia	Final refined product	38	1,37E-08	kg
Arsenic	Final refined product	51	3,59E-11	kg
Benzene	Final refined product	64	2,72E-07	kg
Benzo[a]pyrene	Final refined product	74	1,52E-11	kg
Beryllium	Final refined product	77	1,07E-10	kg
Black Smoke	Final refined product	392	3,73E-07	kg
Cadmium	Final refined product	100	1,26E-11	kg
Carbon Dioxide as CO2	Final refined product	111	0,006046	kg
Carbon Monoxide	Final refined product	122	1,98E-06	kg
Chromium	Final refined product	141	8,88E-11	kg
Copper	Final refined product	156	1,25E-10	kg
Dioxins (PCDD/F)	Final refined product	178	1,45E-15	kg
Hydrofluorocarbons	Final refined product	259	8,36E-08	kg
Hydrogen Chloride	Final refined product	264	2,48E-09	kg

Lead	Final refined product	298	4,69E-10	kg
Manganese	Final refined product	310	8,47E-11	kg
Mercury	Final refined product	315	2,71E-11	kg
Methane	Final refined product	336	3,92E-07	kg
Nickel	Final refined product	369	2,88E-09	kg
Nitrogen Oxides as NO2	Final refined product	380	8,68E-06	kg
Nitrous Oxide	Final refined product	174	7,85E-08	kg
Non Methane VOC	Final refined product	365	8,87E-06	kg
PM10 (Particulate Matter < 10um)	Final refined product	401	5,7E-07	kg
Selenium	Final refined product	469	1,5E-10	kg
Sulphur Dioxide	Final refined product	503	2,17E-05	kg
Tin	Final refined product	528	6,97E-09	kg
Vanadium	Final refined product	551	4,49E-09	kg
Zinc	Final refined product	569	9,73E-10	kg
PAH, polycyclic aromatic hydrocarbons/ air/ high population density	Final refined product	388	2,04E-09	kg
Aluminium, river	Final refined product	1167	2,73E-10	kg
Barium, river	Final refined product	1197	5,46E-10	kg
Boron, river	Final refined product	1218	2,18E-09	kg
Calcium, ion, river	Final refined product	1246	2,73E-07	kg
Chloride, river	Final refined product	1265	4,33E-07	kg
Cyanide, river	Final refined product	1300	9,45E-10	kg
Fluoride, river	Final refined product	1331	2,43E-08	kg
Hydrocarbons, aromatic, river	Final refined product	1351	3,93E-09	kg
Iron, ion, river	Final refined product	1372	2,73E-09	kg
Magnesium, river	Final refined product	1393	1,36E-07	kg
Manganese, river	Final refined product	1398	1,09E-09	kg
Mercury, river	Final refined product	1405	5,46E-13	kg
Molybdenum, river	Final refined product	1419	5,46E-11	kg
Nitrate, river	Final refined product	1433	4,48E-08	kg
Phosphorus, river	Final refined product	1460	2,11E-09	kg
Potassium, ion, river	Final refined product	1468	5,46E-08	kg
Selenium, river	Final refined product	1500	8,17E-11	kg
Silver, ion, river	Final refined product	1509	2,73E-10	kg
Sodium, ion, river	Final refined product	1516	1,64E-06	kg
Sulfide, river	Final refined product	1535	5,46E-10	kg
Suspended solids, unspecified, river	Final refined product	1542	5,46E-08	kg
Toluene, river	Final refined product	1573	5,44E-09	kg
Xylene, river	Final refined product	1597	5,46E-10	kg
Aluminium, ocean	Final refined product	1166	4,74E-10	kg
Barium, ocean	Final refined product	1196	9,47E-10	kg
Boron, ocean	Final refined product	1217	3,8E-09	kg
Calcium, ion, ocean	Final refined product	1245	4,74E-07	kg
Chloride, ocean	Final refined product	1264	7,55E-07	kg
Cyanide, ocean	Final refined product	1299	1,64E-09	kg

Fluoride, ocean	Final refined product	1330	4,25E-08	kg
Hydrocarbons, aromatic, ocean	Final refined product	1350	6,83E-09	kg
Iron, ion, ocean	Final refined product	1371	4,74E-09	kg
Magnesium, ocean	Final refined product	1392	2,37E-07	kg
Manganese, ocean	Final refined product	1397	1,9E-09	kg
Mercury, ocean	Final refined product	1404	9,47E-13	kg
Molybdenum, ocean	Final refined product	1418	9,49E-11	kg
Nitrate, ocean	Final refined product	1432	7,79E-08	kg
Phosphorus, ocean	Final refined product	1459	3,67E-09	kg
Potassium, ion, ocean	Final refined product	1467	9,47E-08	kg
Selenium, ocean	Final refined product	1499	1,42E-10	kg
Sodium, ion, ocean	Final refined product	1515	2,84E-06	kg
Strontium, ocean	Final refined product	1523	6,63E-09	kg
Suspended solids, unspecified, ocean	Final refined product	1541	9,47E-08	kg
t-Butyl methyl ether, ocean	Final refined product	1611	3,01E-09	kg
Vanadium, ion, ocean	Final refined product	1593	2,84E-10	kg
Zinc, ion, ocean	Final refined product	1602	1,63E-09	kg
Ammonium, ion, river	Final refined product	1172	3,63E-08	kg
Ammonium, ion, ocean	Final refined product	1171	6,33E-08	kg
AOX, Adsorbable Organic Halogen as Cl, river	Final refined product	1148	8,77E-11	kg
Benzene, river	Final refined product	1202	1,24E-10	kg
PAH, polycyclic aromatic hydrocarbons, river	Final refined product	1447	8,77E-11	kg
Sulfate, river	Final refined product	1532	1,11E-06	kg
AOX, Adsorbable Organic Halogen as Cl, ocean	Final refined product	1147	1,53E-10	kg
Benzene, ocean	Final refined product	1201	2,16E-10	kg
PAH, polycyclic aromatic hydrocarbons, ocean	Final refined product	1446	1,53E-10	kg
Sulfide, ocean	Final refined product	1534	9,64E-10	kg
Arsenic, ion, river	Final refined product	1186	5,4E-11	kg
Benzene, ethyl-, river	Final refined product	1207	1,08E-12	kg
Cadmium, ion, river	Final refined product	1240	5,4E-11	kg
Chromium, ion, river	Final refined product	1281	1,21E-09	kg
Copper, ion, river	Final refined product	1296	5,4E-11	kg
Lead, river	Final refined product	1382	1,71E-09	kg
Nickel, ion, river	Final refined product	1427	7,11E-11	kg
Strontium, river	Final refined product	1524	3,78E-09	kg
Vanadium, ion, river	Final refined product	1594	1,62E-10	kg
Zinc, ion, river	Final refined product	1603	9,31E-10	kg
Arsenic, ion, ocean	Final refined product	1185	9,39E-11	kg
Benzene, ethyl-, ocean	Final refined product	1206	1,88E-12	kg
Cadmium, ion, ocean	Final refined product	1239	9,39E-11	kg
Chromium, ion, ocean	Final refined product	1280	2,1E-09	kg
Copper, ion, ocean	Final refined product	1295	9,39E-11	kg

Lead, ocean	Final refined product	1381	2,98E-09	kg
Nickel, ion, ocean	Final refined product	1426	1,24E-10	kg
Sulfate, ocean	Final refined product	1531	1,88E-06	kg
Xylene, ocean	Final refined product	1596	9,37E-10	kg
BOD5, Biological Oxygen Demand, river	Final refined product	1191	3,85E-08	kg
DOC, Dissolved Organic Carbon, river	Final refined product	1306	3,75E-10	kg
TOC, Total Organic Carbon, river	Final refined product	1547	1,52E-07	kg
BOD5, Biological Oxygen Demand, ocean	Final refined product	1190	6,67E-08	kg
DOC, Dissolved Organic Carbon, ocean	Final refined product	1305	6,51E-10	kg
Toluene, ocean	Final refined product	1572	1,05E-08	kg
COD, Chemical Oxygen Demand, river	Final refined product	1234	3,88E-07	kg
COD, Chemical Oxygen Demand, ocean	Final refined product	1233	6,76E-07	kg
Hydrocarbons, unspecified, river	Final refined product	1353	2,06E-09	kg
Nitrogen, organic bound, river	Final refined product	1442	9,94E-08	kg
Oils, unspecified, river	Final refined product	1444	2E-08	kg
Hydrocarbons, unspecified, ocean	Final refined product	1352	3,59E-09	kg
Nitrogen, organic bound, ocean	Final refined product	1441	1,73E-07	kg
Oils, unspecified, ocean	Final refined product	1443	3,47E-08	kg
Phenol, river	Final refined product	1450	8,35E-10	kg
Phenol, ocean	Final refined product	1451	1,45E-09	kg
AOX, Adsorbable Organic Halogen as Cl/ water/ unspecified	UK Oil extraction	1149	6,48E-09	kg
Benzene/ air/ unspecified	UK Oil extraction	67	8,68E-12	kg
Benzo(a)pyrene/ air/ unspecified	UK Oil extraction	76	4,35E-14	kg
BOD5, Biological Oxygen Demand/ water/ unspecified	UK Oil extraction	1192	0,001976	kg
Carbon dioxide, fossil/ air/ unspecified	UK Oil extraction	114	0,109056	kg
Carbon monoxide, fossil/ air/ unspecified	UK Oil extraction	125	0,000397	kg
COD, Chemical Oxygen Demand/ water/ unspecified	UK Oil extraction	1235	0,001976	kg
Dinitrogen monoxide/ air/ unspecified	UK Oil extraction	177	5,98E-06	kg
DOC, Dissolved Organic Carbon/ water/ unspecified	UK Oil extraction	1307	0,000545	kg
Heat, waste/ air/ unspecified	UK Oil extraction	240	1,488072	MJ

Helium/ air/ unspecified	UK Oil extraction	243	1,48E-07	kg
Mercury/ air/ unspecified	UK Oil extraction	319	8,92E-11	kg
Methane, bromotrifluoro-, Halon 1301/ air/ low population density	UK Oil extraction	326	4,68E-10	kg
Methane, fossil/ air/ unspecified	UK Oil extraction	339	3,41E-05	kg
Nitrogen oxides/ air/ unspecified	UK Oil extraction	383	0,000187	kg
Nitrogen/ water/ ocean	UK Oil extraction	1438	4,84E-07	kg
NMVOC, non-methane volatile organic compounds, unspecified origin/ air/ unspecified	UK Oil extraction	368	0,000258	kg
Oils, unspecified/ soil/ unspecified	UK Oil extraction	1038	0,000629	kg
Particulates, > 2.5 um, and < 10um/ air/ unspecified	UK Oil extraction	404	1,54E-07	kg
Radon-222/ air/ unspecified	UK Oil extraction	464	0,000107	kBq
Sulfur dioxide/ air/ unspecified	UK Oil extraction	506	0,000193	kg
Sulfur/ water/ unspecified	UK Oil extraction	1539	1,68E-06	kg
TOC, Total Organic Carbon/ water/ unspecified	UK Oil extraction	1548	0,000545	kg