CRADLE-TO-GATE LIFE CYCLE ANALYSIS OF OLEFINS

Final Report

Submitted to:

American Chemistry Council (ACC) Plastics Division

Submitted by:

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PREFACE

This life cycle assessment of olefins was commissioned and funded by the American Chemical Council (ACC) Plastics Division to update the original data in the 2011 report, **Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors**, as well as the U.S. life cycle inventory (LCI) plastics database. The report was made possible through the cooperation of ACC member companies, who provided data for the production of olefins.

This report was prepared for ACC by Franklin Associates, A Division of Eastern Research Group (ERG), Inc. as an independent contractor. This project was managed by Melissa Huff, Senior Life Cycle Assessment (LCA) Analyst and Project Manager. Anne Marie Molen assisted with data collection tasks, modeling, and report and appendix preparation. Mariya Absar aided with research, modeling and report and appendix preparation. Ben Young assisted with research.

Franklin Associates gratefully acknowledges the significant contribution to this project by Mike Levy and Keith Christman of ACC in leading this project. Also acknowledged are the following companies: Chevron Phillips Chemical Corporation, INEOS Olefins, and the Dow Chemical Company, who graciously provided primary Life Cycle Inventory data for olefins production. Their effort in collecting data has added considerably to the quality of this LCA report.

Franklin Associates makes no statements other than those presented within the report.

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LIST OF ACRONYMS

(Alphabetical)

ACC	AMERICAN CHEMISTRY COUNCIL
AP	ACIDIFICATION POTENTIAL
API	AMERICAN PETROLEUM INSTITUTE
BOD	BIOCHEMICAL OXYGEN DEMAND
BOEM	BUREAU OF OCEAN ENERGY MANAGEMENT
BTEX	BENZENE, TOLUENE, ETHYLBENZENE, AND XYLENE
COD	CHEMICAL OXYGEN DEMAND
CFC	CHLOROFLUOROCARBON
DMR	DISCHARGING MONITORING REPORT
EGRID	EMISSIONS & GENERATION RESOURCE INTEGRATED DATABASE
EIA	ENERGY INFORMATION ADMINISTRATION
EP	EUTROPHICATION POTENTIAL
ERG	EASTERN RESEARCH GROUP, INC
EQ	EQUIVALENTS
GHG	GREENHOUSE GAS
GHGRP	GREENHOUSE GAS REPORTING PROGRAM
GJ	GIGAJOULE
GREET	GREENHOUSE GASES, REGULATED EMISSIONS, AND ENERGY USE IN TRANSPORTATION
GWP	GLOBAL WARMING POTENTIAL
HGL	HYDROCARBON GAS LIQUIDS
IPCC	INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
ISO	INTERNATIONAL ORGANIZATION FOR STANDARDIZATION
LCA	LIFE CYCLE ASSESSMENT
LCI	LIFE CYCLE INVENTORY
LCIA	LIFE CYCLE IMPACT ASSESSMENT
LPG	LIQUEFIED PETROLEUM GAS
MJ	MEGAJOULE

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MM	MILLION
NAICS	NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM
NAPAP	NATIONAL ACID PRECIPITATION ASSESSMENT PROGRAM
NETL	NATIONAL ENERGY TECHNOLOGY LABORATORY
NEI	NATIONAL EMISSIONS INVENTORY
NGL	NATURAL GAS LIQUID
NMVOC	NON-METHANE VLOATILE ORGANIC COMPOUNDS
NOAA	NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NREL	NATIONAL RENEWABLE ENERGY LABORATORY
NRU	NITROGEN REJECTION UNIT
ODP	OZONE DEPLETION POTENTIAL
PHMSA	PIPLINE AND HAZARDOUS MATERIALS SAFETY ADMINISTRATION
POCP	PHOTOCHEMICAL SMOG FORMATION
RCRA	RESOURCE CONSERVATION AND RECOVERY ACT
SI	INTERNATIONAL SYSTEM OF UNITS
TRACI	TOOL FOR THE REDUCTION AND ASSESSMENT OF CHEMICAL AND OTHER ENVIRONMENTAL IMPACTS
TRI	TOXIC RELEASE INVENTORY
USGS	UNITED STATES GEOLOGICAL SURVEY
WTE	WASTE-TO-ENERGY INCINERATION

CRADLE-TO-GATE LIFE CYCLE ASSESSMENT OF OLEFINS

INTRODUCTION

This study provides the American Chemical Council (ACC), their members, users of the U.S. LCI Database, and the public at large with information about the life cycle inventory and impacts for the production of olefins including Ethylene, Propylene, Butadiene and Pyrolysis gasoline (Pygas) which are used to create a variety of products in North America.[1] Life cycle assessment (LCA) is recognized as a scientific method for making comprehensive, quantified evaluations of the environmental benefits and tradeoffs commonly for the entire life cycle of a product system, beginning with raw material extraction and continuing through disposition at the end of its useful life as shown in Figure 1 below. This cradle-to-gate LCA includes the life cycle stages shown in the dashed box including the "Raw Materials Acquisition" and "Materials Manufacture" boxes in the figure.
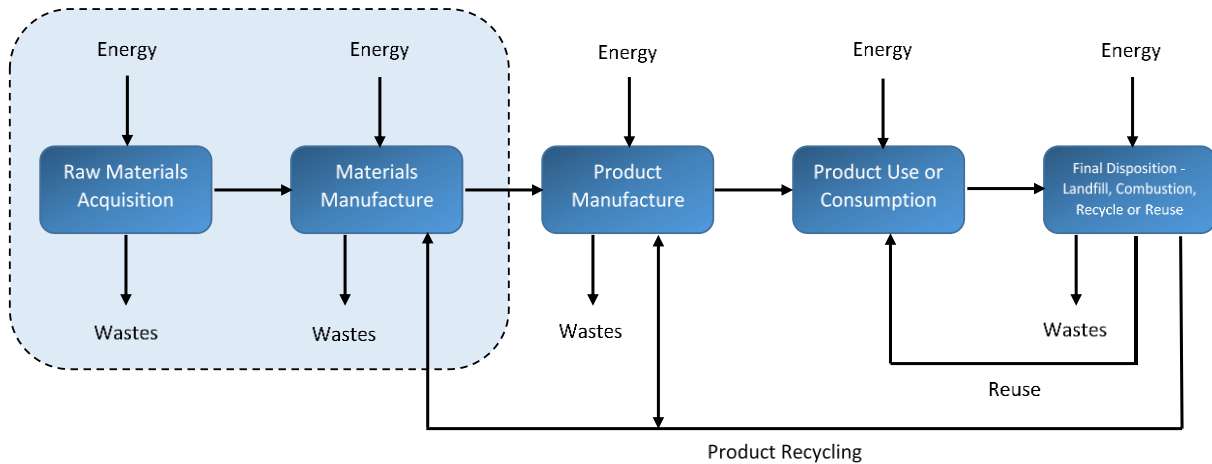

Figure 1. General materials flow for "cradle-to-grave" analysis of a product system. The dashed box indicates the boundaries of this analysis.

The results of this analysis are useful for understanding production-related impacts and are provided in a manner suitable for incorporation into full life cycle assessment studies. The information from an LCA can be used as the basis for further study of the potential improvement of resource use and environmental impacts associated with product systems. It can also pinpoint areas (e.g., material components or processes) where changes would be most beneficial in terms of reducing energy use or potential impacts.

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[1] Butadiene results are available with limited details in some LCI categories. Butadiene's unit process data was not included in this report due to limited data providers. The LCI data for butadiene is considered confidential and will be included with resins that include it as an input material.

A life cycle assessment commonly examines the sequence of steps in the life cycle of a product system, beginning with raw material extraction and continuing through material production, product fabrication, use, reuse or recycling where applicable, and final disposition. This cradle-to-gate life cycle inventory (LCI) and life cycle impact assessment (LCIA) quantifies the total energy requirements, energy sources, water consumption, atmospheric pollutants, waterborne pollutants, and solid waste resulting from the production of olefins. It is considered a cradle-to-gate boundary system because this analysis ends with the olefin production. The system boundaries stop at the olefin production so that the olefin data can be linked to a resin where it is an input material, and then fabrication, use, and end-of-life data to create full life cycle inventories for a variety of products, such as solvents, polymers and lubricants. The method used for this inventory has been conducted following internationally accepted standards for LCI and LCA methodology as outlined in the International Organization for Standardization (ISO) 14040 and 14044 standard documents[2].

This LCA boundary ends at material production. An LCA consists of four phases:

- Goal and scope definition
- Life cycle inventory (LCI)
- Life cycle impact assessment (LCIA)
- Interpretation of results

The LCI identifies and quantifies the material inputs, energy consumption, water consumption, and environmental emissions (atmospheric emissions, waterborne wastes, and solid wastes) over the defined scope of the study. The LCI data for this analysis of Olefins is shown separately as unit processes in the attached Appendix. Those unit processes will be made available to the National Renewable Energy Laboratory (NREL) who maintains the U.S. LCI Database.

In the LCIA phase, the inventory of emissions is classified into categories in which the emissions may contribute to impacts on human health or the environment. Within each impact category, the emissions are then normalized to a common reporting basis, using characterization factors that express the impact of each substance relative to a reference substance.

STUDY GOAL AND SCOPE

In this section, the goal and scope of the study is defined, including information on data sources used and methodology.

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[2]   International Standards Organization. ISO 14040:2006 Environmental management—Life cycle assessment—Principles and framework, ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines.

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STUDY GOAL AND INTENDED USE

The purpose of this LCA is to document the LCI data and then evaluate the environmental profiles of each of the olefins. The intended use of the study results is twofold:

- To provide the LCA community and other interested parties with average North American LCI data for olefins, and
- to provide information about the environmental burdens associated with the production of olefins. The LCA results for the olefins production can be used as a benchmark for evaluating future updated olefins results for North America.

According to ISO 14040 and 14044 standards, a peer review is not required as no comparative assertions of competing materials or products are made in this study.

This report is the property of ACC and may be used by the trade association or members or the general public at ACC's discretion.

FUNCTIONAL UNIT

The function of olefins is their ability to be used in a variety of industrial products, for example, solvents, polymers and lubricants. As the study boundary concludes at the chemical manufacture, a mass functional unit has been chosen. Results for this analysis are shown on a basis of both 1,000 pounds and 1,000 kilograms of each of the olefins produced.

SCOPE AND BOUNDARIES

This LCA quantifies energy and resource use, water consumption, solid waste, and environmental impacts for the following steps in the life cycle of the olefins produced:

- Raw material extraction (e.g., extraction of petroleum and natural gas as feedstocks for olefins production), and incoming transportation for each process, and
- Each of the olefins manufacture, including incoming transportation for each material.

Limited results for butadiene are included in this report due to data not being available from at least 3 producers. Only cradle-to-butadiene totals are available for some LCI results categories. The LCI unit process average for butadiene is confidential and will be included within the averaged resin production LCI data where it is a material input, in concurrent resin LCI averaged data and LCA reports. For example, butadiene and polybutadiene data will be included in the high impact polystyrene averaged LCI dataset.

This report presents LCI results, as well as LCIA results, for the production of olefins split out by ethylene production, propylene production, butadiene production, and pyrolysis gasoline (pygas) production. Due to the use of mass allocation, the LCI data is identical for each olefin at the plant level; however, the weighted average is based on each olefin's individual production amount. This creates distinct averages for each olefin. For butadiene, only two

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data providers produced this chemical in their plants. A butadiene average was created but the unit process LCI data is considered confidential. Tables and figures are provided in the results section of this report for each olefin (ethylene, propylene, butadiene, and pyrolysis gasoline) in each inventory and impact category. Figure 2 presents the flow diagram for the production of olefins. Process descriptions and individual process tables for each box shown process in the flow diagram can be found in the appendix.

Technological Scope – Steam Cracking

The process used in this analysis for manufacturing olefins is the thermal cracking, or steam cracking, of saturated hydrocarbons such as ethane, propane, naphtha, and other gas oils. Although steam cracking has been provided for this analysis, many of the olefins here can be manufactured by a number of technologies. Due to the abundance of propane, ethane, and methane from shale gas, lighter alternative feedstocks are now used more frequently[3]. Coal, biomass and other feedstocks are used in used in smaller proportions to create olefins, but steam cracking will likely remain a leading technology for the manufacture of olefins[4]. Propylene mainly comes from steam cracking or as a by-product of refining, although some propylene is created through propane dehydrogenation (PDH), olefin metathesis, methanol synthesis, and coal to olefins. Butadiene mainly comes from steam cracking with small amounts produced from ethanol[5]. Pyrolysis gas is commonly manufactured in steam crackers, then may be further processed to create a BTX stream used to produce benzene, toluene, and xylenes.

Typical production of ethylene, propylene, and other coproducts begins when hydrocarbons are fed to the cracking furnace. After being pre-heated by a heat exchanger, mixed with steam and then further heated, the hydrocarbon feed is transferred to a reactor. The temperature is again increased to around 800 Celsius, and the cracked gas products are immediately cooled in quench towers using quench oil or quench water. Fuel oil is separated from the main gas stream in a multi-stage centrifugal compressor. The main gas stream then undergoes acid gas removal and drying to remove any moisture that may remain from the quenching process prior to cracked gas compression. The final step involves fractional distillation of the various reaction products and is achieved using a series of distillation columns and hydrogenation reactors.

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[3] Amghizar, Ismaël, et.al. Engineering. New Trends in Olefin Production, March 16, 2017. Vol. 3. pp 171–178.
[4] Ibid.
[5] Dussol,D. et.al. Chemical Engineering Journal. New Insights of Butadiene Production from Ethanol: Elucidation of Concurrent Reaction Pathways and Kinetic Study. November 26, 2019. 123586.
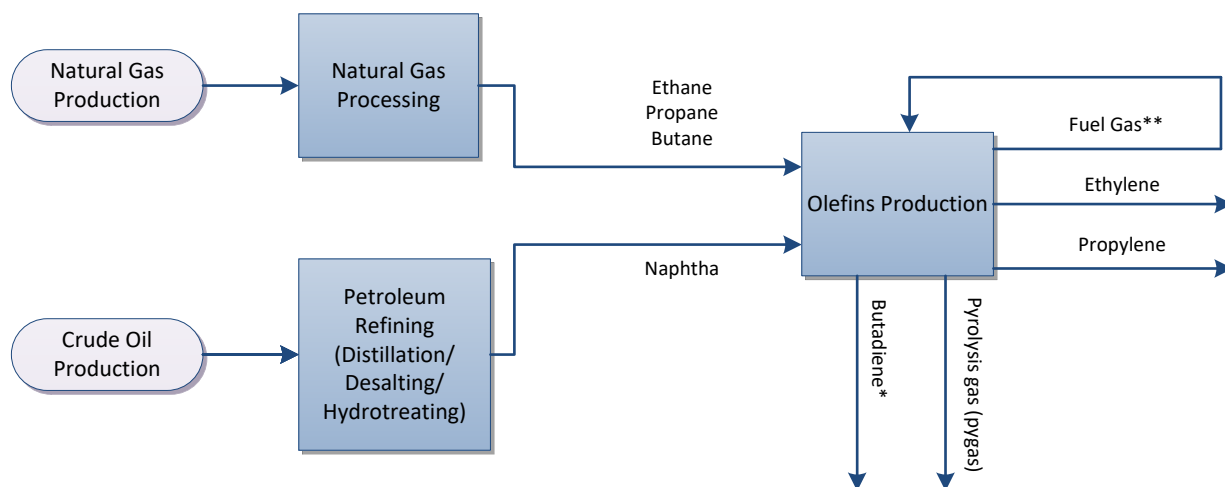
Figure 2. Flow diagram for the Production of Olefins.

*Results for the production of butadiene are included in this report, but unit process data are not shown due to confidentiality.

**Fuel gas used for energy is created from off-gas produced in the process.

Note: Coproduct allocation was given for crude C4's, ethane, hydrogen and acetylene (not shown in the diagram) using mass allocation. Additional coproducts include some fuels created in the process, which are given an energy allocation.

Within the hydrocracker, an offgas is produced from the raw materials entering. A portion of this offgas is processed and used as fuel gas to produce steam for the hydrocracker, while the remaining portion is exported from the hydrocracker as a coproduct. This internally-created energy is included in the analysis by including the production of the raw materials combusted to produce the energy as well as the energy amount attributed to the combustion of those raw materials. Unlike the raw materials that become part of the product output mass, no material feedstock energy is assigned to the raw materials inputs that are combusted within the process. This offgas used within the process is shown as a weight of natural gas and petroleum input to produce the energy.

Temporal and Geographic Scope

Primary data were collected from olefin manufacturers from the year 2015, the most recent full year of olefin production prior to the project initiation date. Companies providing data were given the option to collect data from the year preceding or following 2015 if either year would reflect more typical production conditions. After reviewing individual company data in comparison to the average, each manufacturer verified data from 2015 was representative of an average year for olefin production at their company.

The geographic scope of the analysis is the manufacture of olefins in North America. All olefins data collected were from plants in the United States and Canada and modeled using

North American databases such as the U.S. LCI database and Franklin Associates' private database. The U.S. electricity grid from 2016 was taken from information in Emissions & Generation Resource Integrated Database (eGRID) 2016 database.

Exclusions from the Scope

The following are not included in the study:

- **Miscellaneous materials and additives.** Selected materials such as catalysts, pigments, ancillary materials, or other additives which total less than one percent by weight of the net process inputs are typically not included in assessments. Omitting miscellaneous materials and additives keeps the scope of the study focused. It is possible that production of some substances used in small amounts may be energy and resource intensive or may release toxic emissions; however, the impacts would have to be very large in proportion to their mass in order to significantly affect overall results and conclusions. For this study, no use of resource-intensive or high-toxicity chemicals or additives was identified. Therefore, the results for the resin are not expected to be understated by any significant amount due to substances that may be used in small amounts.
- **Capital equipment, facilities, and infrastructure.** The energy and wastes associated with the manufacture of buildings, roads, pipelines, motor vehicles, industrial machinery, etc. are not included. The energy and emissions associated with production of capital equipment, facilities, and infrastructure generally become negligible when averaged over the total output of product or service provided over their useful lifetimes.
- **Space conditioning.** The fuels and power consumed to heat, cool, and light manufacturing establishments are omitted from the calculations when possible. For manufacturing plants that carry out thermal processing or otherwise consume large amounts of energy, space conditioning energy is quite low compared to process energy. The data collection forms developed for this project specifically requested that the data provider either exclude energy use for space conditioning, or indicate if the reported energy requirements included space conditioning. Energy use for space conditioning, lighting, and other overhead activities is not expected to make a significant contribution to total energy use for the resin system.
- **Support personnel requirements**. The energy and wastes associated with research and development, sales, and administrative personnel or related activities have not been included in this study. Similar to space conditioning, energy requirements and related emissions are assumed to be quite small for support personnel activities.

INVENTORY AND IMPACT ASSESSMENT RESULTS CATEGORIES

The full inventory of emissions generated in an LCA study is lengthy and diverse, making it difficult to interpret emissions profiles in a concise and meaningful manner. LCIAs helps to interpret of the emissions inventory. LCIA is defined in ISO 14044 Section 3.4 as the "phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product." In the LCIA phase, the inventory of emissions is first classified into categories in which the emissions may contribute to impacts on human health or the environment. Within each impact category, the emissions are then normalized to a common reporting basis, using characterization factors that express the impact of each substance relative to a reference substance.

The LCI and LCIA results categories and methods applied in this study are displayed in Table 1. This study addresses global, regional, and local impact categories. For most of the impact categories examined, the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1 method, developed by the United States Environmental Protection Agency (EPA) specific to U.S. conditions and updated in 2012, is employed.[6] For the category of Global Warming Potential (GWP), contributing elementary flows are characterized using factors reported by the Intergovernmental Panel on Climate Change (IPCC) in 2013 with a 100 year time horizon.[7] In addition, the following LCI results are included in the results reported in the analysis:

- Energy demand: this method is a cumulative inventory of all forms of energy used for processing energy, transportation energy, and feedstock energy. This analysis reports both total energy demand and non-renewable energy demand. Renewable and non-renewable energy demand are reported separately to assess consumption of fuel resources that can be depleted, while total energy demand is used as an indicator of overall consumption of resources with energy value. Energy is also categorized by individual fuel types, as well as by process/fuel vs. feedstock energy.
- Total solid waste is assessed as a sum of the inventory values associated with this category. This category is also broken into hazardous and non-hazardous wastes and their end-of-life (e.g. incineration, waste-to-energy, or landfill).
- Water consumption is assessed as a sum of the inventory values associated with this category and does not include any assessment of water scarcity issues.

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[6]   Bare, J. C. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User's Manual; EPA/600/R-12/554 2012.

[7]   IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

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Table 1. Summary of LCI/LCIA Impact Categories

	Impact/Inventory Category	Description	Units (in English and SI)	LCIA/LCI Methodology
LCI Categories	Total energy demand	Measures the total energy from point of extraction; results include both renewable and non-renewable energy sources.	Million (MM) Btu and megajoule (MJ)	Cumulative energy inventory
	Non-renewable energy demand	Measures the fossil and nuclear energy from point of extraction.	MM Btu and MJ	Cumulative energy inventory
	Renewable energy demand	Measures the hydropower, solar, wind, and other renewables, including landfill gas use.	MM Btu and MJ	Cumulative energy inventory
	Solid waste by weight	Measures quantity of fuel and process waste to a specific fate (e.g., landfill, waste-to-energy (WTE)) for final disposal on a mass basis	Lb and kg	Cumulative solid waste inventory
	Water consumption	Freshwater withdrawals which are evaporated, incorporated into products and waste, transferred to different watersheds, or disposed into the land or sea after usage	Gallons and Liters	Cumulative water consumption inventory
LCIA Categories	Global warming potential	Represents the heat trapping capacity of the greenhouse gases. Important emissions: CO_2 fossil, CH_4, N_2O	Lb CO_2 equivalents (eq) and kg CO_2 equivalents (eq)	IPCC (2013) GWP 100a*
	Acidification potential	Quantifies the acidifying effect of substances on their environment. Important emissions: SO_2, NO_x, NH_3, HCl, HF, H_2S	Lb SO_2 eq and kg SO_2 eq	TRACI v2.1
	Eutrophication potential	Assesses impacts from excessive load of macro-nutrients to the environment. Important emissions: NH_3, NO_x, chemical oxygen demand (COD) and biochemical oxygen demand (BOD), N and P compounds	Lb N eq and kg N eq	TRACI v2.1
	Ozone depletion potential	Measures stratospheric ozone depletion. Important emissions: chlorofluorocarbon (CFC) compounds and halons	Lb CFC-11 eq and kg CFC-11 eq	TRACI v2.1
	Smog formation potential	Determines the formation of reactive substances (e.g. tropospheric ozone) that cause harm to human health and vegetation. Important emissions: NO_x, benzene, toluene, ethylbenzene, xylene (BTEX), non-methane volatile organic compound	Lb kg O_3 eq and kg O_3 eq	TRACI v2.1

	Impact/Inventory Category	Description	Units (in English and SI)	LCIA/LCI Methodology
		(NMVOC), CH_4, C_2H_6, C_4H_{10}, C_3H_8, C_6H_{14}, acetylene, Et-OH, formaldehyde		

DATA SOURCES

The purpose of this study is to develop a life cycle profile for olefins using the most recent data available for each process. A weighted average was calculated for the olefins data (production for the year 2015) collected for this analysis. Secondary data was researched in 2017 for crude oil extraction and refining and natural gas production and processing. All included processes are shown in Figure 2.

LCI data for the production of olefins, including ethylene, propylene and pyrolysis gasoline, were collected from three producers (ten plants) in North America – all in the United States. Only two of the data providers (3 plants) also produced butadiene, which limited the results provided in this report for that olefin. All companies provided data for the year 2015. A weighted average was calculated from the data collected and used to develop the LCA model. The captured ethylene production amount is approximately 10 percent[8] of the ethylene production in the U.S. in 2015. The captured propylene production amount is estimated to be 4 percent[9] of the total propylene production in the U.S. in 2015. Propylene, pyrolysis gasoline and butadiene are coproducts of ethylene production, and a mass basis was used to allocate the environmental burdens among these coproducts. For coproducts sold for fuel use in other processes, these were treated as an avoided fuel product and were given credits based on the fuel they would replace.

The data for the remaining raw material and intermediate materials used to produce Olefins are from secondary sources. All process descriptions and LCI data for unit processes are provided in the Appendix at the end of this report.

DATA QUALITY ASSESSMENT

ISO 14044:2006 lists a number of data quality requirements that should be addressed for studies intended for use in public comparative assertions. The data quality goals for this analysis were to use data that are (1) geographically representative for the olefins based on the locations where material sourcing and production take place, and (2) representative of current industry practices in these regions. As described in the previous section, three companies each provided current, geographically representative data for all primary data

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[8] Oil and Gas Journal, 2017. US olefins industry prepares for waves of new capacity. March 6, 2017. Vol. 115, Issue 3. Calculations performed by Franklin Associates.

[9] Ibid.

collected for this LCA. Butadiene was sold by only 2 of the 3 olefin producers and may be considered lower data quality than the other olefins in this report due to the limited amount of butadiene captured.

The remaining datasets were either updated using geographical and technologically relevant data from government or privately available statistics/studies within the US or drawn from either The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model or ecoinvent[10]. Datasets from ecoinvent were adapted to U.S. conditions to the extent possible (e.g., by using U.S. average grid electricity to model production of process electricity reported in the European data sets). Petroleum refining is the only process that includes some small additives that use data from secondary sources. The data sets used were the most current and most geographically and technologically relevant data sets available during the data collection phase of the project.

Consistency, Completeness, Precision: Data evaluation procedures and criteria were applied consistently to all primary data provided by the participating producers for all data collected. All primary data obtained specifically for this study were considered the most representative available for the systems studied. Data sets were reviewed for completeness and material balances, and follow-up was conducted as needed to resolve any questions about the input and output flows, process technology, etc. The aggregated averaged datasets were also reviewed by the providing companies as compared to the provided dataset. Companies were requested to review whether their data were complete and to comment about their or the average dataset.

Representativeness: The largest portion of olefins manufactured in North America are produced through steam cracking of hydrocarbons. Olefin producers from the United States and Canada provided data from steam cracker facilities using technology ranging from old to state-of the art. Ten steam cracker facilities producing olefins provided data from plants using technology considered old, average, and state-of-the-art compared to other facilities producing olefins. Of the ten plants, two plants were using older technology, five plants were using average technology and three plants were using state-of the art technology in 2015.

Primary data were collected from olefin manufacturers from the year 2015, the most recent full year of olefin production prior to the project initiation date. Companies providing data were given the option to collect data from the year preceding or following 2015 if either year would reflect more typical production conditions. After reviewing individual company data in comparison to the average, each manufacturer verified data from 2015 was a representative year for olefin production in North America.

LCI data from the sources of input materials specific to each company providing data was not available for this analysis. Average U.S. statistics were used were used for refined

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10   Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: <http://link.springer.com/10.1007/s11367-016-1087-8> [Accessed Sept, 2018].

petroleum products and processed natural gas to develop the average olefins unit process data. As impacts from crude oil and natural gas may vary depending on transportation requirements some variability in data and impact on LCA results should be expected.

The average olefins unit process data was based on the best available data at the time the study was conducted. As in all LCA studies, the ability to develop a representative average is determined by the number of companies willing to participate. Although the captured ethylene and propylene production amounts (10 percent and 4 percent, respectively) is low compared to total ethylene and propylene production in North America, data from this analysis was used to develop the most representative average for olefins production in 2015 as was possible.

Reproducibility: To maximize transparency and reproducibility, the report identifies specific data sources, assumptions, and approaches used in the analysis to the extent possible; however, reproducibility of study results is limited to some extent by the need to protect certain data sets that were judged to be high quality and representative data sets for modeling purposes but could not be shown due to confidentiality.

Uncertainty: Uncertainty issues and uncertainty thresholds applied in interpreting study results are described in the following section.

DATA ACCURACY AND UNCERTAINTY

In LCA studies with thousands of numeric data points used in the calculations, the accuracy of the data and how it affects conclusions is truly a complex subject, and one that does not lend itself to standard error analysis techniques. Techniques such as Monte Carlo analysis can be used to assess study uncertainty, but the greatest challenge is the lack of uncertainty data or probability distributions for key parameters, which are often only available as single point estimates. However, steps are taken to ensure the reliability of data and results, as previously described.

The accuracy of the environmental results depends on the accuracy of the numbers that are combined to arrive at that conclusion. For some processes, the data sets are based on actual plant data reported by plant personnel, while other data sets may be based on engineering estimates or secondary data sources. Primary data collected from actual facilities are considered the best available data for representing industry operations. In this study, primary data were used to model the steam cracking of the olefins. All data received were carefully evaluated with a number of question and answer rounds before compiling the production-weighted average data sets used to generate results. Each Olefins data provider reviewed their dataset in comparison to the weighted average of all companies. Revisions were made from the comments and revised data provided during the review. Supporting background data were drawn from credible, widely used databases including the US LCI database, GREET, NETL, and Ecoinvent.

METHOD

The LCA has been conducted following internationally accepted standards for LCA as outlined in the ISO 14040 and 14044 standards, which provide guidance and requirements for conducting LCA studies. However, for some specific aspects of LCA, the ISO standards have some flexibility and allow for choices to be made. The following sections describe the approach to each issue used in this study. Many of these issues are specific to the olefins produced at the steam crackers.

Raw Materials Use for Internal Energy in Steam Crackers

Some of the raw material inputs to the steam cracker create gases that are combusted to provide energy for the steam cracker, decreasing the amount of purchased energy required for the reaction. Data providers listed this energy as fuel gas or offgas and, in many cases, supplied the heating value of this gas. Using this information, Franklin Associates calculated the amount of raw material combusted within the steam cracker to produce this utilized energy source.

This internally-created energy is included in the analysis by including the production of the raw materials combusted to produce the energy as well as the energy amount attributed to the combustion of those raw materials. Unlike the raw materials that become part of the product output mass, no material feedstock energy is assigned to the raw materials inputs that are combusted within the process.

Coproduct Allocation

An important feature of life cycle inventories is that the quantification of inputs and outputs are related to a specific amount of useful output from a process. However, it is sometimes difficult or impossible to identify which inputs and outputs are associated with individual products of interest resulting from a single process (or process sequence) that produces multiple useful products. The practice of allocating inputs and outputs among multiple products from a process is often referred to as coproduct allocation.

Co-product allocation is done out of necessity when raw materials and emissions cannot be directly attributed to one of several product outputs from a system. It has long been recognized that the practice of allocating the environmental burdens among the coproducts is less desirable than being able to identify which inputs lead to specific outputs. In this study, co-product allocations are necessary because of multiple useful outputs from the "upstream" chemical process involved in producing Ethylene.

Franklin Associates follows the guidelines for allocating the environmental burdens among the coproducts as shown in the ISO 14044:2006 standard on life cycle assessment requirements and guidelines[11]. In this standard, the preferred hierarchy for handling

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[11] International Standards Organization. ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines.

allocation is (1) avoid allocation where possible, (2) allocate flows based on direct physical relationships to product outputs, (3) use some other relationship between elementary flows and product output. No single allocation method is suitable for every scenario. As described in ISO 14044 section 4.3.4.2, when allocation cannot be avoided, the preferred partitioning approach should reflect the underlying physical relationships between the different products or functions.

Material Coproducts

Some processes lend themselves to physical allocation because they have physical parameters that provide a good representation of the environmental burdens of each co-product. Examples of various allocation methods are mass, stoichiometric, elemental, reaction enthalpy, and economic allocation. Simple mass and enthalpy allocation have been chosen as the common forms of allocation in this analysis. However, these allocation methods were not chosen as a default choice but made on a case by case basis after due consideration of the chemistry and basis for production.

Material coproducts were created in all the intermediate chemical process steps collected for this analysis, as well as the primary Ethylene production. The material coproducts from ethylene production for all plants included propylene, pyrolysis gasoline, butadiene, ethane, hydrogen, acetylene, crude benzene, and small amounts of various heavy end products.

A portion of the inputs and outputs calculated for the coproducts were removed from the total inputs and outputs, so that the remaining inputs and outputs only represented the main product in each unit process. The ratio of the mass of the coproduct over the total mass output was removed from the total inputs and outputs of the process, and the remaining inputs and outputs are allocated over the material products (Equation 1).

$$[IO] \times \left(1 - \frac{M_{CP}}{M_{Total}}\right) = [IO] \text{ } _{attributed \text{ } to \text{ } remaining \text{ } products} \qquad \text{(Equation 1)}$$

where
IO = Input/Output Matrix to produce all products/coproducts
M_{CP} = Mass of Coproduct
M_{Total} = Mass of all Products and Coproducts

Energy Coproducts Exported from System Boundaries

Some of the unit processes produce energy either as a fuel coproduct or as steam created from the process that is sent to another plant for use. To the extent possible, system expansion to avoid allocation was used as the preferred approach in the ISO 14044:2006 standard. Fuels or steam exported from the boundaries of the system would replace purchased fuels for another process outside the system. System expansion credits were given for avoiding the energy-equivalent quantity of fuel production and combustion displaced by the exported coproduct energy.

Electricity Grid Fuel Profile

Electricity production and distribution systems in North America are interlinked. Users of electricity, in general, cannot specify the fuels used to produce their share of the electric power grid. Data for this analysis was collected from plants in the United States. The U.S. average fuel consumption by electrical utilities was used for the electricity within this analysis. This electricity data set uses the Emissions & Generation Resource Integrated Database (eGRID) 2016 database[12].

Electricity generated on-site at a manufacturing facility is represented in the process data by the fuels used to produce it. If a portion of on-site generated electricity is sold to the electricity grid, credits for sold on-site electricity are accounted for in the calculations for the fuel mix.

Electricity/Heat Cogeneration

Cogeneration is the use of steam for generation of both electricity and heat. The most common configuration is to generate high temperature steam in a cogeneration boiler and use that steam to generate electricity. The steam exiting the electricity turbines is then used as a process heat source for other operations. Significant energy savings occur because in a conventional operation, the steam exiting the electricity generation process is condensed, and the heat is dissipated to the environment.

For LCI purposes, the fuel consumed and the emissions generated by the cogeneration boiler need to be allocated to the two energy-consuming processes: electricity generation and subsequent process steam. An energy basis was used for allocation in this analysis.

In order to allocate fuel consumption and environmental emissions to both electricity and steam generation, the share of the two forms of energy (electrical and thermal) produced must be correlated to the quantity of fuel consumed by the boiler. Data on the quantity of fuel consumed and the associated environmental emissions from the combustion of the fuel, the amount of electricity generated, and the thermal output of the steam exiting electricity generation must be known in order to allocate fuel consumption and environmental emissions accordingly. These three types of data are discussed below.

1. **Fuels consumed and emissions generated by the boiler:** The majority of data providers for this study reported natural gas as the fuel used for cogeneration. According to 2016 industry statistics, natural gas accounted for 75 percent of industrial cogeneration, while coal and biomass accounted for the largest portion of the remaining fuels used [13].

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[12] Online database found at: https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid

[13] US Department of Energy. *Combined Heat and Power (CHP) Technical Potential in the United States.* March 2016.

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2. **Kilowatt-Hours of Electricity Generated:** In this analysis, the data providers reported the kilowatt-hours of electricity from cogeneration. The Btu of fuel required for this electricity generation was calculated by multiplying the kilowatt-hours of electricity by 6,826 Btu/kWh (which utilizes a thermal to electrical conversion efficiency of 50 percent). This Btu value was then divided by the Btu value of fuel consumed in the cogeneration boiler to determine the electricity allocation factor.

   The 50 percent conversion efficiency was an estimate after reviewing EIA fuel consumption and electricity net generation data from cogeneration plants in 2016.[14] The straight average conversion efficiency for 2016 for electricity production in cogeneration plants within this database is a little more than 55 percent; however, the range of efficiency calculated per individual cogeneration plant was 23% to 87%. The 50 percent estimate of conversion efficiency was used previously in the 2011 database and so was estimated for continued use within this analysis, due to the variability of the individual cogeneration plants. Unit process data for cogeneration of electricity is provided by kWh, so that a change of efficiency could easily be applied during modeling.

3. **Thermal Output of Steam Exiting Electricity Generation:** In this analysis, the data providers stated the pounds and pressure of steam from cogeneration. The thermal output (in Btu) of this steam was calculated from enthalpy tables (in most cases steam ranged from 1,000 to 1,200 Btu/lb). An efficiency of 80 percent was used for the industrial boiler to calculate the amount of fuel used. This Btu value was then divided by the Btu value of fuel consumed in the cogeneration boiler to determine the steam allocation factor. The 80 percent efficiency used is common for a conventional natural gas boiler, which should not change when considering the steam portion of the cogeneration system. Pounds of steam, temperature and pressure were provided by participating plants. Steam tables were used to calculate energy amounts, which was divided by the efficiency and converted to natural gas amounts in cubic feet.

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[14] U.S. Department of Energy, The Energy Information Administration (EIA). *EIA-923 Monthly Generation and Fuel Consumption Time Series File, 2016 Final Revision*

LIFE CYCLE INVENTORY AND IMPACT ASSESSMENT RESULTS

This section presents baseline results for the following LCI and LCIA results for both 1,000 pounds and 1,000 kilograms of the olefins (ethylene, propylene, pyrolysis gasoline and butadiene[15]) included:

Life cycle inventory results:
- Cumulative energy demand
- Non-renewable energy demand
- Renewable energy demand
- Total energy by fuel type
- Solid waste by weight
- Water consumption

Life cycle impact assessment results:
- Global warming potential
- Acidification potential
- Eutrophication potential
- Ozone depletion potential
- Smog formation potential

Throughout the results sections, the tables and figures break system results out into the following unit processes, for the three olefins considered:

- Natural gas extraction and processing,
- Oil extraction and refining, and
- Olefin production.

Due to the use of mass allocation, the LCI data is identical for each olefin at the plant level; however, the weighted average is based on the individual production amount of each olefin. This creates distinct averages for each olefin. Tables and figures are provided for each olefin (ethylene, propylene, pygas, and butadiene) in each inventory and impact category section in this report. The term "pygas" is used interchangeably with pyrolysis gasoline in the results sections.

The phrases "cradle-to-" and "system" are defined as including all of the raw and intermediate chemicals required for the production of the chemical stated in the term (e.g. cradle-to-ethylene and ethylene system are interchangeable). The phrase "gate-to-gate" is defined as including only the onsite process and no upstream or downstream inputs and emissions.

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[15] Results are not available in detail as is for the other olefins, or confidential data would be at risk if presented.

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ENERGY DEMAND

Cumulative Energy Demand

Cumulative energy demand results include all renewable and non-renewable energy sources used for process and transportation energy, as well as material feedstock energy. Process energy includes direct use of fuels, including the use of fossil fuels, hydropower, nuclear, wind, solar, and other energy sources to generate electricity used by processes. Fuel energy is the energy necessary to create and transport the fuels to the processes. The feedstock energy is the energy content of the resources removed from nature and used as material feedstocks for the olefins production (e.g., the energy content of oil and gas used as material feedstocks).

The average total energy required to produce ethylene is 29.7 million Btu per 1,000 pounds of ethylene or 69.2 gigajoule (GJ) per 1,000 kilograms of ethylene. Table 2 shows total energy demand for the life cycle of ethylene production. The production energy has been split out from the energy required for natural gas and petroleum extraction and processing. Less than a quarter of the total energy is required to produce the ethylene on-site. Approximately 69 percent of the total energy is required to produce natural gas used as a feedstock to the ethylene production, while about 7 percent is needed to produce the petroleum feedstock for the ethylene produced. The feedstock sources for ethylene is approximately 90 percent from natural gas and 10 percent from oil.

The average total energy required to produce propylene is 30.2 million Btu per 1,000 pounds of propylene or 70.2 GJ per 1,000 kilograms of propylene. Table 3 shows total energy demand for the life cycle of propylene production. The production energy has been split out from the energy required for natural gas and petroleum extraction and processing. A little less than a quarter of the total energy is required to produce the propylene on-site. Approximately 66 percent of the total energy is required to produce natural gas used as a feedstock to the propylene production, while 10 percent is needed to produce the petroleum feedstock for the propylene produced. Approximately 86 percent of the feedstock material for propylene comes from natural gas and 14 percent of the feedstock material comes from oil.

The average total energy required to produce Pyrolysis gasoline is 30 million Btu per 1,000 pounds of pyrolysis gasoline or 69.9 GJ per 1,000 kilograms of pyrolysis gasoline. Table 4 shows total energy demand for the life cycle of pyrolysis gasoline production. The production energy has been split out from the energy required for natural gas and petroleum extraction and processing. Almost a quarter of the total energy is required to produce pygas on-site. Approximately 68 percent of the total energy is required to produce natural gas used as a feedstock to the pygas production, while 8 percent is required to produce the petroleum feedstock for the pygas produced. The feedstock sources for pygas is 89 percent from natural gas and 11 percent from oil.

Table 2. Total Energy Demand for Ethylene

	Basis: 1,000 pounds		
	Total Energy	Non-Renewable Energy	Renewable Energy
	MM Btu	*MM Btu*	*MM Btu*
Natural gas extraction and processing	20.5	20.5	0.007
Petroleum extraction and refining	2.13	2.13	0.003
Ethylene Production	7.15	7.12	0.022
Total	**29.7**	**29.7**	**0.032**
	Basis: 1,000 kilograms		
	Total Energy	Non-Renewable Energy	Renewable Energy
	GJ	*GJ*	*GJ*
Natural gas extraction and processing	47.6	47.6	0.017
Petroleum extraction and refining	4.95	4.95	0.008
Ethylene Production	16.6	16.6	0.050
Total	**69.2**	**69.1**	**0.075**
	Percentage		
	Total Energy	Non-Renewable Energy	Renewable Energy
	%	*%*	*%*
Natural gas extraction and processing	68.8%	68.8%	0.02%
Petroleum extraction and refining	7.2%	7.2%	0.01%
Ethylene Production	24.0%	23.9%	0.07%
Total	**100%**	**99.9%**	**0.1%**

Table 3. Total Energy Demand for Propylene

	Basis: 1,000 pounds		
	Total Energy	Non-Renewable Energy	Renewable Energy
	MM Btu	*MM Btu*	*MM Btu*
Natural gas extraction and processing	19.8	19.8	0.007
Petroleum extraction and refining	2.98	2.98	0.005
Propylene Production	7.42	7.40	0.019
Total	**30.2**	**30.2**	**0.031**
	Basis: 1,000 kilograms		
	Total Energy	Non-Renewable Energy	Renewable Energy
	GJ	*GJ*	*GJ*
Natural gas extraction and processing	46.0	46.0	0.016
Petroleum extraction and refining	6.94	6.93	0.011
Propylene Production	17.3	17.2	0.045
Total	**70.2**	**70.1**	**0.072**
	Percentage		
	Total Energy	Non-Renewable Energy	Renewable Energy
	%	*%*	*%*
Natural gas extraction and processing	65.5%	65.5%	0.02%
Petroleum extraction and refining	9.9%	9.9%	0.02%
Propylene Production	24.6%	24.5%	0.06%
Total	**100%**	**99.9%**	**0.1%**

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Table 4. Total Energy Demand for Pyrolysis Gasoline

	Basis: 1,000 pounds		
	Total Energy	Non-Renewable Energy	Renewable Energy
	MM Btu	*MM Btu*	*MM Btu*
Natural gas extraction and processing	20.2	20.2	0.007
Petroleum extraction and refining	2.34	2.34	0.004
Pyrolysis gasoline Production	7.45	7.43	0.018
Total	**30.0**	**30.0**	**0.029**
	Basis: 1,000 kilograms		
	Total Energy	Non-Renewable Energy	Renewable Energy
	GJ	*GJ*	*GJ*
Natural gas extraction and processing	47.1	47.1	0.017
Petroleum extraction and refining	5.45	5.44	0.008
Pyrolysis gasoline Production	17.3	17.3	0.042
Total	**69.9**	**69.8**	**0.067**
	Percentage		
	Total Energy	Non-Renewable Energy	Renewable Energy
	%	*%*	*%*
Natural gas extraction and processing	67.4%	67.4%	0.02%
Petroleum extraction and refining	7.8%	7.8%	0.01%
Pyrolysis gasoline Production	24.8%	24.7%	0.06%
Total	**100%**	**99.9%**	**0.1%**

The average total energy required to produce Butadiene is 27.3 million Btu per 1,000 pounds of butadiene or 63.5 GJ per 1,000 kilograms of butadiene. Table 5 shows total energy demand for the life cycle of butadiene production. The production energy was not able to be split out from the energy required for natural gas and petroleum extraction and processing due to confidentiality issues. The feedstock sources for butadiene is 77 percent from natural gas and 23 percent from oil.

Table 5. Total Energy Demand for Butadiene

	Total Energy	Non-Renewable Energy	Renewable Energy
MM Btu per 1,000 pounds	27.3	27.2	0.059
GJ per 1,000 kilograms	63.5	63.4	0.14
Percentage	100%	99.8%	0.2%

Non-renewable energy demand includes the use of fossil fuels (petroleum, natural gas, and coal) for process energy, transportation energy, and as material feedstocks (e.g., oil and gas used as feedstocks for the production of the olefins), as well as use of uranium to generate the share of nuclear energy in the average U.S. kWh. For all four olefins, more than 99.8 percent of the total energy comes from non-renewable sources. The landfill gas used for process energy at the olefins plant and electricity derived from renewable energy sources (primarily hydropower, as well as wind, solar, and other sources) comprise the renewable energy demand. Of the renewable energy (up to 0.2 percent of the total energy) for all four olefins, approximately half comes from a split of hydropower and other renewable sources (geothermal, solar, etc.) from electricity production, with the remaining half coming from landfill gas.

Of the total energy needed to produce ethylene, propylene and pygas, 72 percent of the total energy for the olefins production comes from material feedstock energy, with the remaining from fuel or process energy. The energy representing natural gas and petroleum used as raw material inputs for the production of olefins are included in the Natural gas and Petroleum extraction and processing system amounts in Table 2, Table 3 and Table 4. The energy from these raw materials are called material feedstock energy. Figure 3, Figure 4 and Figure 5 provides a graphical perspective of the percentages of total energy required for material feedstock energy versus the process and fuel energy amounts needed to produce the ethylene, propylene, and pygas. The material feedstock for butadiene is somewhat higher than for the other olefins, as shown in Figure 6. This is due to a higher use of petroleum-based input materials than used for the other olefins considered here. As a limited number of companies and plants have provided data for butadiene, no further detailed analysis can be provided.
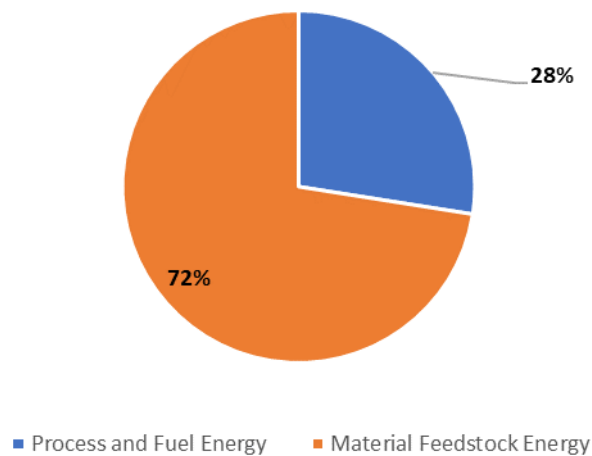

28%

72%

■ Process and Fuel Energy   ■ Material Feedstock Energy

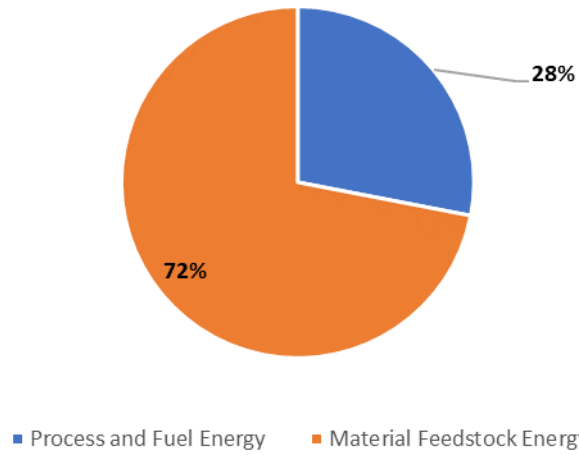**Figure 3. Process/Fuel and Material Feedstock Percentages for Ethylene**

Figure 4. Process/Fuel and Material Feedstock Percentages for Propylene
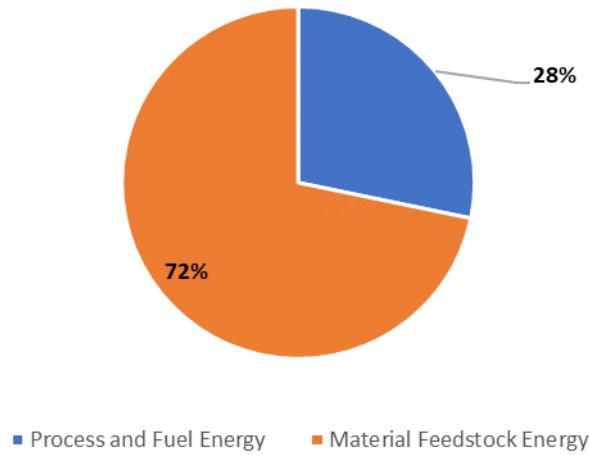

Figure 5. Process/Fuel and Material Feedstock Percentages for Pyrolysis Gasoline
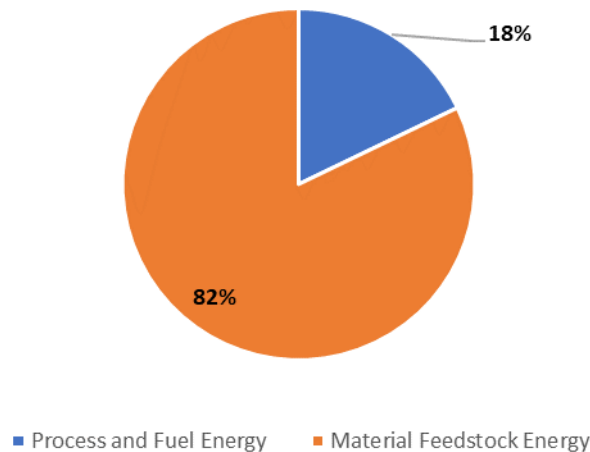
Figure 6. Process/Fuel and Material Feedstock Percentages for Butadiene

Energy Demand by Fuel Type

The total energy demand by fuel type for ethylene, propylene, pygas, and butadiene is shown respectively in Table 6 through 9 and their percentage mix is shown in Figure 7 through 10. For the each of the olefins production, natural gas and petroleum fuels together make up more than 98 percent of the total energy used. As shown in Figure 3 through 6, this is partially due to the material feedstock energy used to create the olefins. These material feedstock fuels are part of the energy shown in the natural gas and petroleum split out in the following tables and figures. The production energy for each olefin in the following tables and figures represents the energy required for transportation of raw materials to olefin manufacturers, the energy required to produce the olefin itself, and the production of the fuels needed to manufacture the olefins.

Petroleum-based fuels (e.g. diesel fuel) are the dominant energy source for transportation. Natural gas and other fuel types, such as hydropower, nuclear and other (geothermal, wind, etc.) are used to generate purchased electricity. Other renewables also include a small amount of landfill gas used for process energy in olefins production.

Of the results for ethylene production shown in Table 6 and Figure 7, over 90 percent of the energy used (63.2 GJ/69.2 GJ) is from natural gas. This is true specifically at the ethylene plant as well (15.6 GJ/16.6 GJ). Approximately 30 percent of the natural gas is combusted at the plant. Fifty percent of this natural gas is used as a raw material for creating fuel gas used as an energy source during olefins manufacture. The remainder of this natural gas is used either as a transport fuel for pipeline or for creation of the electricity used at the plant. Petroleum comprises only 1 percent (0.78 GJ/16.6 GJ) of the fuel used for ethylene production at the plant; only 4 percent of that 1 percent of petroleum is combusted during transport, with almost 95 percent used to produce the petroleum inputs used to create a fuel gas used as an energy source. The coal use shown is combusted for electricity use. The 2016 U.S. electricity grid is used for this study. In this grid, approximately 30 percent of the

electricity production in the US uses coal as a fuel source. Other main fuels sources for electricity include natural gas (34%) and uranium (19.8%) with the remaining sources of electricity each at less than 10 percent of the grid. The hydropower, nuclear, and other energy are all used to create electricity. Other energy does include a small amount of landfill gas used as an energy source at the ethylene plant.

Table 6. Energy Demand by Fuel Type for Ethylene

	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
Basis: 1,000 pounds							
	MM Btu	MM Btu	MM Btu	MM Btu	MM Btu	MM Btu	MM Btu
Natural gas extraction and processing	20.5	20.4	0.008	0.04	0.03	0.003	0.004
Petroleum extraction and refining	2.13	0.12	1.97	0.02	0.01	0.001	0.002
Ethylene Production	7.15	6.69	0.34	0.06	0.04	0.004	0.018
Total	**29.7**	**27.2**	**2.32**	**0.12**	**0.08**	**0.009**	**0.024**
Basis: 1,000 kilograms							
	GJ	GJ	GJ	GJ	GJ	GJ	GJ
Natural gas extraction and processing	47.6	47.4	0.019	0.10	0.07	0.007	0.010
Petroleum extraction and refining	4.95	0.28	4.59	0.05	0.03	0.003	0.004
Ethylene Production	16.6	15.6	0.78	0.14	0.09	0.010	0.041
Total	**69.2**	**63.2**	**5.39**	**0.28**	**0.19**	**0.020**	**0.055**
Percentage of Total							
	%	%	%	%	%	%	%
Natural gas extraction and processing	68.8%	68.5%	0.03%	0.15%	0.10%	0.01%	0.01%
Petroleum extraction and refining	7.2%	0.4%	6.64%	0.07%	0.04%	0.005%	0.006%
Ethylene Production	24.0%	22.5%	1.13%	0.20%	0.13%	0.01%	0.06%
Total	**100%**	**91.4%**	**7.8%**	**0.4%**	**0.3%**	**0.03%**	**0.08%**
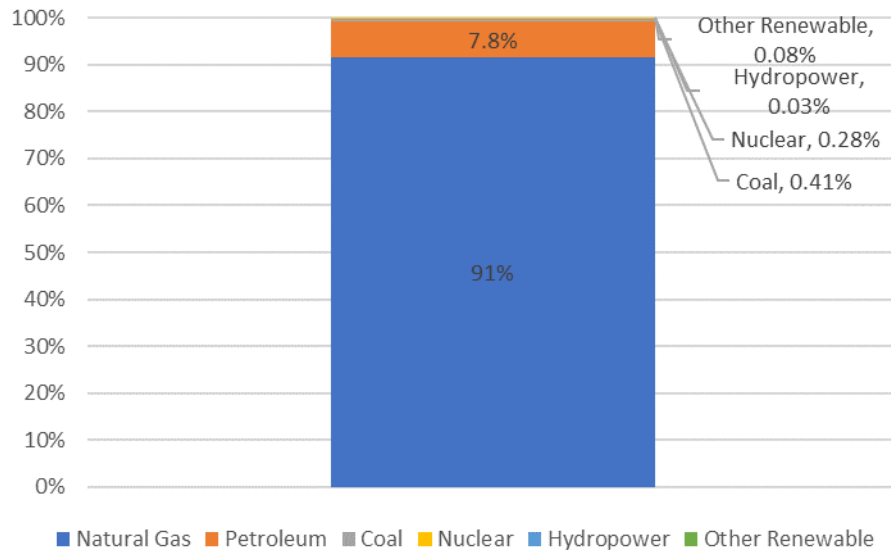
Figure 7. Percentage of Energy Separated by Fuel Type for Ethylene

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Of the results for propylene production shown in Table 7 and Figure 8, a little less than 90 percent of the total energy used (62 GJ/70.2 GJ) is from natural gas. Again, this is true at the propylene plant as well since over 90 percent (15.8 GJ/17.3 GJ) comes from natural gas. As in the ethylene production, petroleum comprises less than 1 percent (1.16 GJ/17.3 GJ) of the fuel used for propylene production. The uses of the remaining fuels are adjacent to the uses when ethylene is the main product and have been discussed previously. The differences in the percentages of natural gas and petroleum as materials and fuels as compared to the other olefins are due to the weightings of the plant averages using production amounts of each of the olefins.

Of the results for pyrolysis gasoline production shown in Table 8 and Figure 9, around 90 percent of the total energy used (63.4 GJ/69.9 GJ) is from natural gas. This is also true at the pygas plant where 93 percent of the energy used (16.2 GJ/17.3 GJ) is from natural gas. Petroleum comprises less than 1 percent (0.87 GJ/17.3 GJ) of the fuel used for pygas production. The uses of the remaining fuels are adjacent to the uses when ethylene is the main product and have been discussed previously. The differences in the percentages of natural gas and petroleum as materials and fuels as compared to the other olefins are due to the weightings of the plant averages using production amounts of each of the olefins.

Table 7. Energy Demand by Fuel Type for Propylene

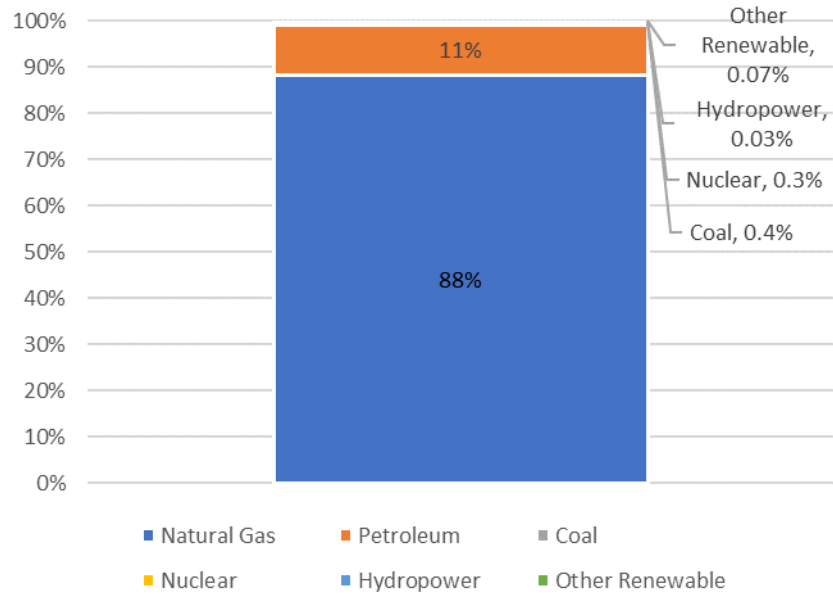|	Basis: 1,000 pounds						
	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
	MM Btu	MM Btu	MM Btu	MM Btu	MM Btu	MM Btu	MM Btu
Natural gas extraction and processing	19.8	19.7	0.008	0.04	0.03	0.0030	0.0042
Petroleum extraction and refining	2.98	0.17	2.76	0.03	0.02	0.0020	0.0024
Propylene Production	7.42	6.79	0.50	0.07	0.04	0.0046	0.0149
Total	30.2	26.7	3.27	0.14	0.09	0.0096	0.0215
	Basis: 1,000 kilograms						
	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
	GJ	GJ	GJ	GJ	GJ	GJ	GJ
Natural gas extraction and processing	46.0	45.8	0.018	0.10	0.07	0.007	0.010
Petroleum extraction and refining	6.94	0.39	6.43	0.07	0.04	0.005	0.006
Propylene Production	17.3	15.8	1.16	0.15	0.10	0.011	0.035
Total	70.2	62.0	7.61	0.31	0.21	0.022	0.050
	Percentage of Total						
	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
	%	%	%	%	%	%	%
Natural gas extraction and processing	65.5%	65.3%	0.0%	0.14%	0.09%	0.01%	0.01%
Petroleum extraction and refining	9.9%	0.6%	9.16%	0.09%	0.06%	0.01%	0.01%
Propylene Production	24.6%	22.5%	1.65%	0.22%	0.15%	0.02%	0.05%
Total	100%	88.3%	10.8%	0.45%	0.30%	0.03%	0.07%

Figure 8. Percentage of Energy Separated by Fuel Type for Propylene

Table 8. Energy Demand by Fuel Type for Pyrolysis gasoline

|	Basis: 1,000 pounds						
	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
	MM Btu	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*
Natural gas extraction and processing	20.2	20.2	0.008	0.04	0.03	0.003	0.004
Petroleum extraction and refining	2.34	0.13	2.17	0.02	0.01	0.002	0.002
Pyrolysis gasoline Production	7.45	6.96	0.38	0.06	0.04	0.004	0.014
Total	**30.0**	**27.2**	**2.56**	**0.12**	**0.08**	**0.009**	**0.020**
	Basis: 1,000 kilograms						
	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
	GJ	*GJ*	*GJ*	*GJ*	*GJ*	*GJ*	*GJ*
Natural gas extraction and processing	47.1	46.9	0.019	0.10	0.07	0.01	0.010
Petroleum extraction and refining	5.45	0.30	5.05	0.05	0.03	0.004	0.004
Pyrolysis gasoline Production	17.3	16.2	0.87	0.14	0.09	0.010	0.033
Total	**69.9**	**63.4**	**5.94**	**0.29**	**0.19**	**0.020**	**0.048**
	Percentage of Total						
	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
	%	*%*	*%*	*%*	*%*	*%*	*%*
Natural gas extraction and processing	67.4%	67.1%	0.03%	0.14%	0.10%	0.01%	0.01%
Petroleum extraction and refining	7.8%	0.4%	7.2%	0.07%	0.05%	0.01%	0.01%
Pyrolysis gasoline Production	24.8%	23.2%	1.2%	0.19%	0.13%	0.01%	0.05%
Total	**100%**	**90.7%**	**8.5%**	**0.41%**	**0.28%**	**0.03%**	**0.07%**
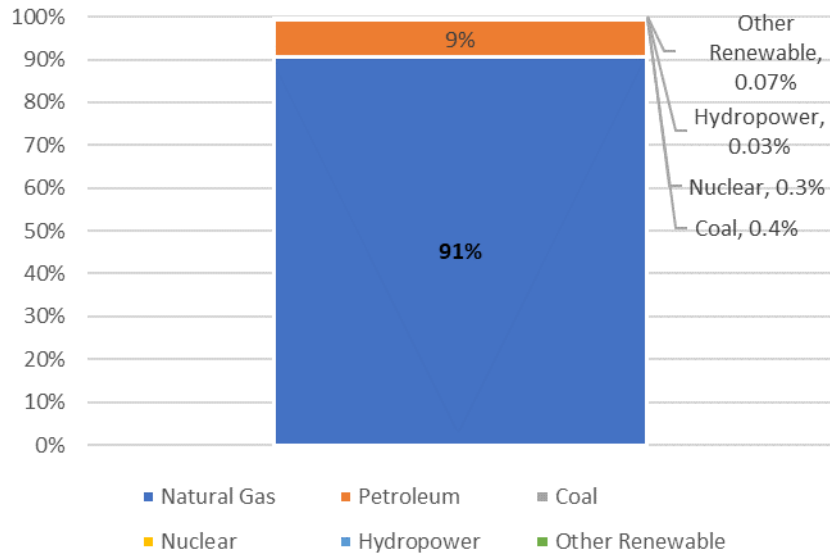
Figure 9. Percentage of Energy Separated by Fuel Type for Pyrolysis Gasoline

Of the results for butadiene production shown in Table 9 and Figure 10, approximately 78 percent of the total energy used (49.6 GJ/63.5 GJ) is from natural gas. Petroleum comprises a little more then 20 percent (13.0 GJ/63.5 GJ) of the total energy. The uses of the remaining fuels are proportionate to the uses when ethylene is the main product and have been discussed previously. The differences in the percentages of natural gas and petroleum as materials and fuels as compared to the other olefins are due to the weightings of the plant averages using production amounts of each of the olefins. The plants producing butadiene use a higher amount of petroleum products as raw materials to the olefins plant than the other olefins. The average of these plants also included a higher amount of fuel gas piped to other processes, which increased the credit given to the butadiene system for avoided fuels.

Table 9. Energy Demand by Fuel Type for Butadiene

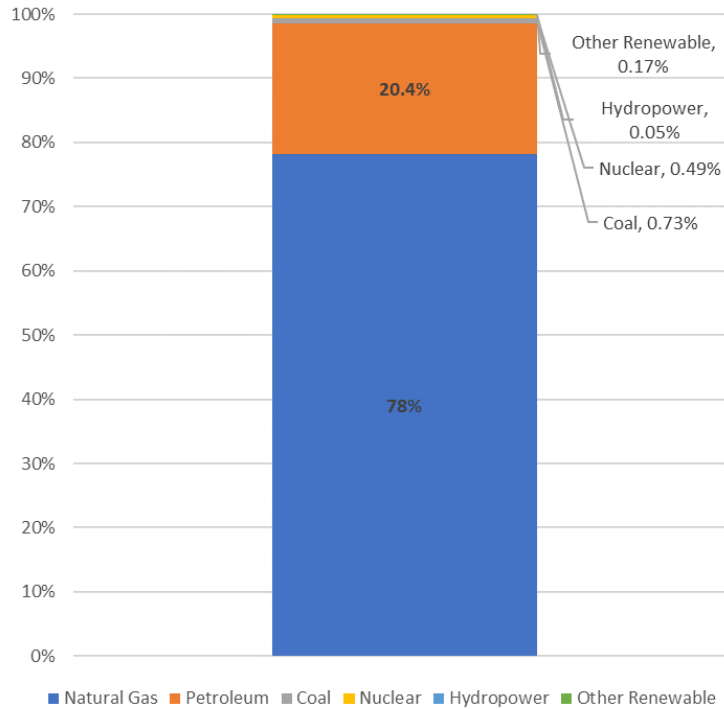|	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
MM Btu per 1,000 pounds	27.3	21.3	5.58	0.20	0.13	0.014	0.046
GJ per 1,000 kilograms	63.5	49.6	13.0	0.46	0.31	0.033	0.11
Percentage	100%	78.1%	20.4%	0.73%	0.49%	0.05%	0.17%

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Figure 10. Percentage of Energy Separated by Fuel Type for Butadiene

SOLID WASTE

Solid waste results include the following types of wastes:

- **Process wastes** that are generated by the various processes from raw material acquisition through production of the olefins (e.g., sludges and residues from chemical reactions and material processing steps)
- **Fuel-related wastes** from the production and combustion of fuels used for process energy and transportation energy (e.g., refinery wastes, coal combustion ash)

No postconsumer wastes of the olefins are included in this analysis.

The process solid waste, those wastes produced directly from the olefin production processes, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately where possible. Solid wastes from fuel combustion (e.g. ash) are assumed to be landfilled.

Results for solid waste by weight for the ethylene system are shown in
Table 10 and Figure 11. The solid wastes have been separated into hazardous and non-hazardous waste categories, as well as by the incoming main materials (natural gas extraction and processing as well as petroleum extraction and refining) and the ethylene plant. As shown in Figure 11, thirty-eight percent of the total solid waste is created during the ethylene unit process from fuel combusted or as a process solid waste during the

ethylene production. The remaining 65 percent of the solid waste comes from the production of incoming materials used to produce ethylene. Approximately 90 percent of the incoming materials are a product of natural gas processing, which creates 51 percent of the total solid wastes. The crude oil refining products comprise 10 percent of the incoming materials to the ethylene plant, which creates 11 percent of the total solid wastes. From these amounts, we can see that more solid wastes are created from the petroleum system as compared to the natural gas system.

Solid wastes are shown separated by hazardous and non-hazardous wastes in Table 10. This separation was done only where primary data was collected, or if a secondary data source was clear that the solid waste was of a hazardous nature. All of the process solid wastes from oil and natural gas were classified as non-hazardous due to exclusions found in The Resource Conservation and Recovery Act (RCRA) hazardous wastes regulations or other EPA hazardous wastes regulations. Only 2.9 percent of the total solid wastes were considered hazardous wastes, which are attributed entirely to ethylene unit process.

Table 10 also provides a breakout of the total solid wastes by the disposal fate. Solid waste sent to recycling was not included in this breakout. Almost all hazardous waste at the ethylene plant is incinerated with no energy capture, with only a minute amount landfilled. Focusing on the non-hazardous solid waste produced, the largest amount of the solid waste is landfilled, while 12 percent is incinerated, and a minute amount (0.001%) sent to waste-to-energy.

Table 10. Total Solid Wastes for Ethylene

|	Basis: 1,000 pounds								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	lb	*lb*	*lb*	*lb*	*lb*	*lb*	*lb*	*lb*	*lb*
Natural gas extraction and processing	24.9	0	0	0	0	0	0	24.9	24.9
Petroleum extraction and refining	5.18	0	0	0	0	0	0	5.18	5.18
Ethylene Production	18.4	0	1.40	0.0031	1.40	6.1E-04	6.00	11.0	17.0
Total	**48.4**	**0**	**1.40**	**0.0031**	**1.40**	**6.1E-04**	**6.00**	**41.0**	**47.0**
	Basis: 1,000 kilograms								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	kg	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*
Natural gas extraction and processing	24.9	0	0	0	0	0	0	24.9	24.9
Petroleum extraction and refining	5.18	0	0	0	0	0	0	5.18	5.18
Ethylene Production	18.4	0	1.40	0.0031	1.40	6.1E-04	6.00	11.0	17.0
Total	**48.4**	**0**	**1.40**	**0.0031**	**1.40**	**6.1E-04**	**6.00**	**41.0**	**47.0**
	Percentage of Total								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	%	%	%	%	%	%	%	%	%
Natural gas extraction and processing	51%	0%	0%	0%	0%	0%	0%	51%	51.4%
Petroleum extraction and refining	11%	0%	0%	0%	0%	0%	0%	11%	10.7%
Ethylene Production	38%	0%	2.9%	0.006%	2.9%	0.001%	12%	23%	35.0%
Total	**100%**	**0%**	**2.9%**	**0.006%**	**2.9%**	**0.001%**	**12%**	**85%**	**97.1%**
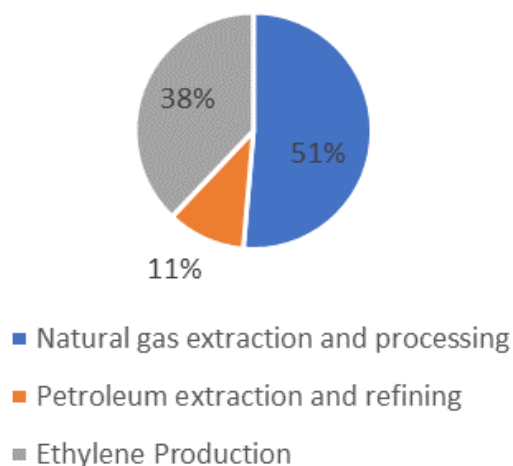
Figure 11. Percentage of Total Solid Wastes for the Ethylene System

Results for solid waste by weight for the propylene production system are shown in Table 11 and Figure 12. As was done for the ethylene system, the solid wastes have been separated into hazardous and non-hazardous waste categories, as well as by the natural gas and petroleum systems and the propylene plant. In Figure 12, thirty-seven percent of the total solid waste is created during the propylene unit process from fuel combusted or as a process solid waste during the propylene production. The remaining 63 percent of the solid waste comes from the production of incoming materials used to produce propylene. Approximately 86 percent of the incoming materials are a product of natural gas processing, which creates 48 percent of the total solid wastes. The crude oil refining products comprise 14 percent of the incoming materials to the propylene plant, which creates 15 percent of the total solid wastes. As in the ethylene system, the same conclusion that more solid wastes are created from the petroleum system as compared to the natural gas system can be drawn.

From the propylene production system only 2.7 percent of the total solid wastes were considered process hazardous wastes which are attributed entirely to the propylene unit process with none coming from the natural gas or petroleum extraction and processing due to the same reasoning as discussed previously for ethylene.

Table 11. Solid Wastes for Propylene

	Basis: 1,000 pounds								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	lb	lb	lb	lb	lb	lb	lb	lb	lb
Natural gas extraction and processing	24.1	0	0	0	0	0	0	24.1	24.1
Petroleum extraction and refining	7.26	0	0	0	0	0	0	7.26	7.26
Propylene Production	18.7	0	1.33	3.5E-03	1.33	5.8E-04	5.70	11.6	17.3
Total	**50.0**	**0**	**1.33**	**3.5E-03**	**1.33**	**5.8E-04**	**5.70**	**43.0**	**48.7**
	Basis: 1,000 kilograms								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	kg	kg	kg	kg	kg	kg	kg	kg	kg
Natural gas extraction and processing	24.1	0	0	0	0	0	0	24.1	24.1
Petroleum extraction and refining	7.26	0	0	0	0	0	0	7.26	7.26
Propylene Production	18.7	0	1.33	3.5E-03	1.33	5.8E-04	5.70	11.6	17.3
Total	**50.0**	**0**	**1.33**	**3.5E-03**	**1.33**	**5.8E-04**	**5.70**	**43.0**	**48.7**
	Percentage of Total								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	%	%	%	%	%	%	%	%	%
Natural gas extraction and processing	48.1%	0%	0%	0%	0%	0%	0%	48%	48%
Petroleum extraction and refining	14.5%	0%	0%	0%	0%	0%	0%	15%	15%
Propylene Production	37.4%	0%	2.7%	0.007%	2.7%	0.0012%	11%	23%	35%
Total	**100%**	**0%**	**2.7%**	**0.007%**	**2.7%**	**0.0012%**	**11%**	**86%**	**97.3%**

Table 11 also provides a breakout of the total solid wastes by the disposal fate. Solid waste sent to recycling was not included in this breakout. Almost all hazardous waste at the propylene plant is incinerated with no energy capture, with only a minute amount landfilled. Of the non-hazardous solid waste produced, 82 percent is landfilled, 17 percent is incinerated, and a minute amount (0.001%) sent to waste-to-energy.
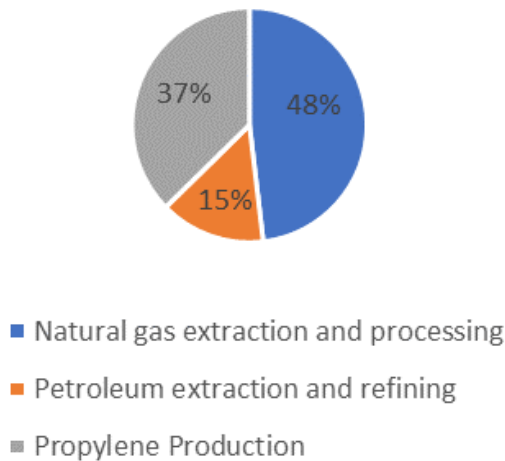

- Natural gas extraction and processing
- Petroleum extraction and refining
- Propylene Production

Figure 12. Percentage of Total Solid Wastes for the Propylene System

Results for solid waste by weight for the pyrolysis gasoline production system are shown in Table 12 and Figure 13. As for the previous olefins, solid wastes have been separated into hazardous and non-hazardous waste categories, as well as by the natural gas and petroleum systems and the pygas plant. In Figure 13, approximately 39 percent of the total solid waste is during the pygas unit process from fuel combusted or as a process solid waste during the pygas production. The remaining 61 percent of the solid waste comes from the production of incoming materials used to produce pyrolysis gasoline. Approximately 89 percent of the incoming materials are a product of natural gas processing, which creates over 49 percent of the total solid wastes. The crude oil refining products comprise 10 percent of the incoming materials to the pygas plant, which creates 11 percent of the total solid wastes. As in the ethylene system, the same conclusion that more solid wastes are created from the petroleum system as compared to the natural gas system can be drawn.

Table 12. Solid Wastes for Pyrolysis Gasoline

|	Basis: 1,000 pounds								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	lb	lb	lb	lb	lb	lb	lb	lb	lb
Natural gas extraction and processing	24.6	0	0	0	0	0	0	24.6	24.6
Petroleum extraction and refining	5.70	0	0	0	0	0	0	5.70	5.70
Pyrolysis gasoline production	19.3	0	1.50	3.0E-03	1.50	6.6E-04	6.50	11.3	17.8
Total	**49.6**	**0**	**1.50**	**3.0E-03**	**1.50**	**6.6E-04**	**6.50**	**41.6**	**48.1**
	Basis: 1,000 kilograms								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	kg	kg	kg	kg	kg	kg	kg	kg	kg
Natural gas extraction and processing	24.6	0	0	0	0	0	0	24.6	24.6
Petroleum extraction and refining	5.70	0	0	0	0	0	0	5.70	5.70
Pyrolysis gasoline Production	19.3	0	1.50	3.0E-03	1.50	6.6E-04	6.50	11.3	17.8
Total	**49.6**	**0**	**1.50**	**3.0E-03**	**1.50**	**6.6E-04**	**6.50**	**41.6**	**48.1**
	Percentage of Total								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	%	%	%	%	%	%	%	%	%
Natural gas extraction and processing	49.6%	0%	0%	0%	0%	0%	0%	50%	50%
Petroleum extraction and refining	11.5%	0%	0%	0%	0%	0%	0%	11%	11%
Pyrolysis gasoline Production	38.9%	0%	3.0%	0.006%	3.0%	0.001%	13%	23%	36%
Total	**100%**	**0%**	**3.0%**	**0.006%**	**3.0%**	**0.001%**	**13%**	**84%**	**97%**
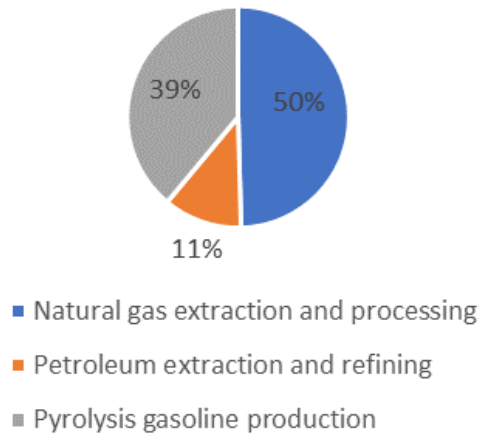
Figure 13. Percentage of Total Solid Wastes for the Pygas System

From the Pyrolysis gasoline production system only 3 percent of the total solid wastes were considered process hazardous wastes which are attributed entirely to the pygas unit process with none coming from the natural gas or petroleum extraction and processing due to the same reasoning as discussed previously.

Figure 13 also provides a breakout of the total solid wastes by the disposal fate. Solid waste sent to recycling was not included in this breakout. Almost all hazardous waste at the pygas plant is incinerated with no energy capture, with only a minute amount landfilled. Of the non-hazardous solid waste produced, 87 percent is landfilled, 13 percent is incinerated, and a minute amount (0.001%) sent to waste-to-energy.

Total solid waste by weight for the butadiene production system are shown in Table 13. Due to confidentiality issues, the solid wastes are not able to be separated out for analysis as for the previous olefins. This total solid waste includes both hazardous and non-hazardous wastes going to waste-to-energy, incineration and landfills. No detailed analysis can be provided due to confidentiality issues.

Table 13. Solid Wastes for Butadiene

	Total Solid Waste	
	Basis: 1,000 Pounds	Basis: 1,000 kilograms
	lb	*kg*
Cradle-to-Butadiene Total	**44.3**	**44.3**

WATER CONSUMPTION

Consumptive use of water in this study includes freshwater that is withdrawn from a water source or watershed and not returned to that source. Consumptive water use includes water consumed in chemical reactions, water that is incorporated into a product or waste stream, water that becomes evaporative loss, and water that is discharged to a different watershed or water body than the one from which it was withdrawn. Water consumption results shown for each life cycle stage include process water consumption as well as water consumption associated with production of the electricity and fuels used in that stage. Electricity-related water consumption includes evaporative losses associated with thermal generation of electricity from fossil and nuclear fuels, as well as evaporative losses due to establishment of dams for hydropower.

Water consumption results for ethylene are shown in Table 14 and Figure 14. The ethylene production dominates the consumption of water within the ethylene system when compared to the natural gas and petroleum extraction and processing inputs. The largest amount of this water, 60 percent of the total, is consumed at the ethylene plant. The olefins primary water consumption data does include some plants that release water to a different watershed than the initial water source, which is considered consumption in the methodology used. The remaining 10 percent of the water consumption shown during ethylene production comes from production of the fuels used, including 2 percent from electricity, which is mostly hydropower use. Almost 19 percent of the water consumed comes from the extraction and processing of natural gas necessary to create input materials to the olefins plant, which coincides with 90 percent of the incoming material to the plant. The remaining 12 percent is consumed during the extraction and refining of crude oil used to produce input materials to the olefins plant, which coincides with 10 percent of the incoming material to the plant.

Table 14. Water Consumption for Ethylene

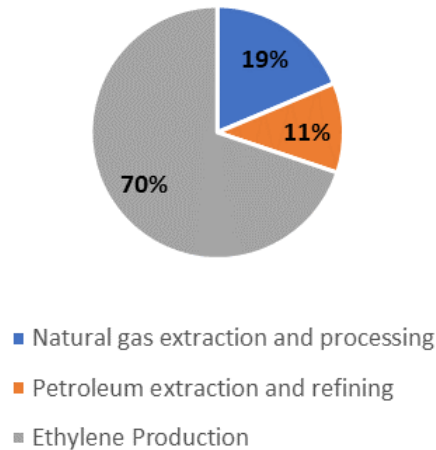|	Total Water Consumption		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	Gallons	*Liters*	*%*
Natural gas extraction and processing	130	1,089	18.7%
Petroleum extraction and refining	80.3	670	11.5%
Ethylene Production	488	4,077	69.9%
Total	**699**	**5,837**	**100%**

Figure 14. Water Consumption for Ethylene

Water consumption results for propylene are shown in Table 15 and Figure 15. The propylene manufacturing process dominates the consumption of water within the propylene system as compared to the natural gas and petroleum material inputs. Fifty-seven percent of the water is consumed at the propylene plant. The olefins primary water consumption data does include some plants that release water to a different watershed than the initial water source, which is considered consumption in the methodology used. The remaining 10 percent of the water consumption associated with propylene production comes from production of the fuels used, including 2 percent from electricity, which is mainly hydropower use. Almost 18 percent of the water consumed comes from the extraction and processing of natural gas necessary to create input materials to the olefins plant. The remaining 16 percent is consumed during the extraction and refining of crude oil used to produce input materials to the olefins plant. The amount of water consumption from petroleum inputs is higher for propylene as compared to ethylene due to higher use of petroleum products used as material inputs at plants producing more propylene.

Table 15. Water Consumption for Propylene

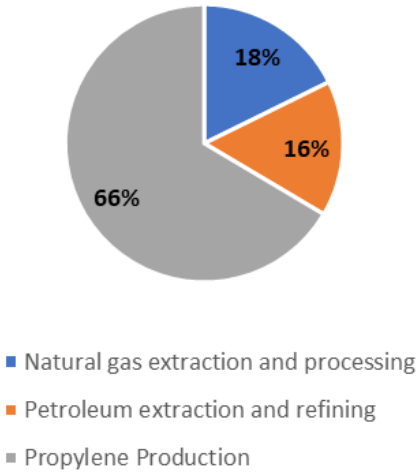|	Total Water Consumption		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	Gallons	*Liters*	*%*
Natural gas extraction and processing	126	1,053	17.7%
Petroleum extraction and refining	112	939	15.8%
Propylene Production	473	3,949	66.5%
Total	**711**	**5,940**	**100%**

Figure 15. Water Consumption for Propylene

Water consumption results for pyrolysis gasoline are shown in Table 16 and Figure 16. The pyrolysis gasoline manufacturing process dominates the consumption of water within the pygas system as compared to the natural gas and petroleum material inputs. Fifty-eight percent of the water is consumed at the pygas plant. The olefins primary water consumption data does include some plants that release water to a different watershed than the initial water source, which is considered consumption in the methodology used. A little more than 10 percent of the pygas production comes from production of the fuels used, including almost 2 percent from electricity, which is mostly hydropower use. The extraction and processing of natural gas requires almost 19 percent of the water consumption to create input materials to the olefins plant. The remaining 13 percent is consumed during the extraction and refining of crude oil used to produce input materials to the olefins plant. Approximately 89 percent of input materials for pygas come from natural gas products, while petroleum products make up the remaining 11 percent.

Table 16. Water Consumption for Pyrolysis Gasoline

	Total Water Consumption		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	Gallons	*Liters*	*%*
Natural gas extraction and processing	129	1,077	18.5%
Petroleum extraction and refining	88.3	737	12.7%
Pyrolysis gasoline Production	479	4,001	68.8%
Total	**696**	**5,815**	**100%**
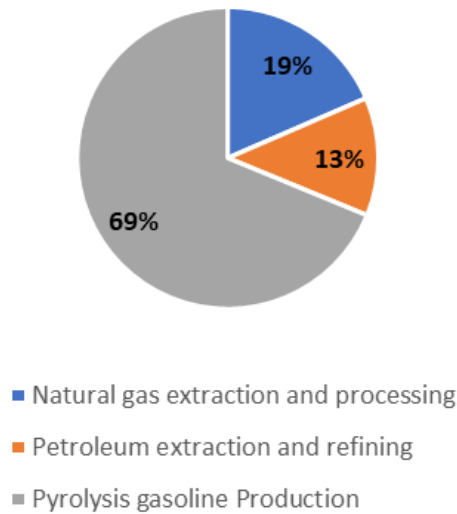
Figure 16. Water Consumption for Pyrolysis Gasoline

Total water consumption results for the butadiene production system are shown in Table 17. Due to confidentiality issues, the water consumption details are not able to be separated out for analysis as for the previous olefins. The olefins primary water consumption data does include some plants that release water to a different watershed than the initial water source, which is considered consumption in the methodology used. No detailed analysis can be provided due to confidentiality issues.

Table 17. Water Consumption for Butadiene

	Total Water Consumption	
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**
	Gallons	*Liters*
Cradle-to-Butadiene Total	712	5,949

GLOBAL WARMING POTENTIAL

The primary atmospheric emissions reported in this analysis that contribute over 99 percent of the total global warming potential for each system are fossil fuel-derived carbon dioxide, methane and nitrous oxide. Other contributors include some HCFCs and CFCs, but these contribute less than 1 percent of the total shown. The main greenhouse gas emissions are mainly combustion. In the primary data collected for olefins, combustion emissions from flare have been included as process emissions and so their totals may be overstated by small amounts due to the inclusion of combustion of fuel used during the flare. Data providers were

asked to estimate percentages of greenhouse gases from flare from that of the combustion of fuels. Any non-fossil carbon dioxide emissions, such as those from the burning of wood-derived fuel, is a return of carbon dioxide to the atmosphere in the same form as it was originally removed from the atmosphere during the biomass growth cycle; therefore, any carbon dioxide emissions from combustion or decomposition of biomass-derived products are not considered a net contributor to global warming.

The 100-year global warming potential (GWP) factors for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2013[16] are: fossil carbon dioxide 1, fossil methane 28, and nitrous oxide 265. The GWP factor for a substance represents the relative global warming contribution of a pound of that substance compared to a pound of carbon dioxide. The weights of each greenhouse gas are multiplied by its GWP factor to arrive at the total GWP results. Although normally GWP results are closely related to the energy results, the feedstock energy is not associated with GWP due to the sequestration of the feedstock material within the olefin. It is the potential energy associated with the feedstock material, which is not combusted to create greenhouse gases.

Table 18 and Figure 17 show life cycle GWP results for ethylene. Of the total, 31 percent of the GWP for the ethylene system are attributed to emissions from the natural gas and petroleum input material production. The largest amount of the GWP is created by the production of ethylene, which accounts for 69 percent of the total GWP. Thirteen percent of the total GWP are emissions associated with fuel use and combustion for ethylene production. The remaining 56 percent comes specifically from the release of greenhouse gases at the ethylene plant.

Table 18. Global Warming Potential for Ethylene

	Global Warming Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CO2 eq	*kg CO2 eq*	*%*
Natural gas extraction and processing	310	310	25.1%
Petroleum extraction and refining	78.5	78.5	6.3%
Ethylene Production	850	850	68.6%
Total	**1,239**	**1,239**	**100%**

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[16] IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Figure 17. Global Warming Potential for Ethylene

Table 19 and Figure 18 show life cycle GWP results for propylene. About 33 percent of the greenhouse gas emissions and GWP for the propylene production system are attributed to natural gas and crude oil extraction and processing emissions. Of the processes, the production of propylene accounts for 67 percent of the total GWP results, out of which 12 percent are emissions associated with fuel production and combustion for propylene production, with the remaining greenhouse gases considered process emissions or from flare.

Table 19. Global Warming Potential for Propylene

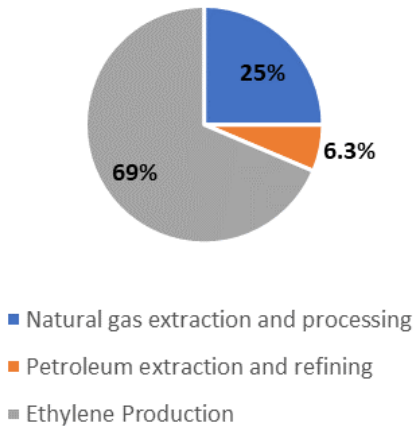|	Global Warming Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb CO2 eq	*kg CO2 eq*	*%*
Natural gas extraction and processing	300	300	24%
Petroleum extraction and refining	110	110	8.7%
Propylene Production	847	847	67%
Total	**1,257**	**1,257**	**100%**
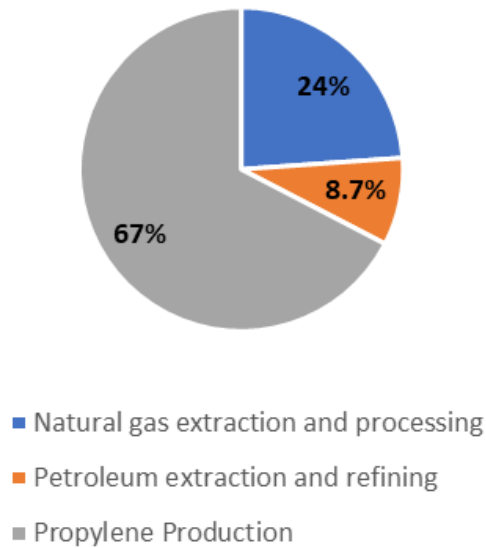
Figure 18. Global Warming Potential for Propylene

Table 20 and Figure 19 show life cycle GWP results for pyrolysis gasoline. About 32 percent of the greenhouse gas emissions and GWP for the pyrolysis gasoline system are attributed to natural gas and crude oil extraction and processing emissions. Of the total GWP, a little more than 68 percent comes from the production of pygas, and from this 12 percent are emissions associated with fuel production and combustion for pygas production, with the remaining greenhouse gas emissions considered from the process or flare.

Table 20. Global Warming Potential for Pyrolysis Gasoline

	Global Warming Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CO2 eq	kg CO2 eq	%
Natural gas extraction and processing	307	307	24.6%
Petroleum extraction and refining	86.4	86.4	6.9%
Pyrolysis gasoline Production	856	856	68.5%
Total	**1,249**	**1,249**	**100%**
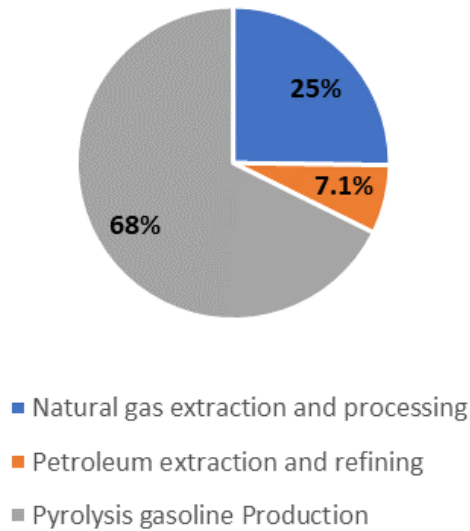
Figure 19. Global Warming Potential for Pyrolysis Gasoline

Table 21and Figure 20 show life cycle GWP results for butadiene. Approximately 40 percent of the greenhouse gas emissions and GWP for the butadiene system are attributed to natural gas and crude oil extraction and processing emissions. Of the total GWP, 60 percent comes from the production of butadiene. These emissions are associated with fuel production and combustion for butadiene production as well as greenhouse gas emissions from the process or flare.

Table 21. Global Warming Potential for Butadiene

	Global Warming Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CO2 eq	kg CO2 eq	%
Natural gas extraction and processing	279	279	23.7%
Petroleum extraction and refining	188	188	16.0%
Butadiene Production	711	711	60.3%
Total	**1,179**	**1,179**	**100%**

24%

16%

60%

- Natural gas extraction and processing
- Petroleum extraction and refining
- Butadiene Production
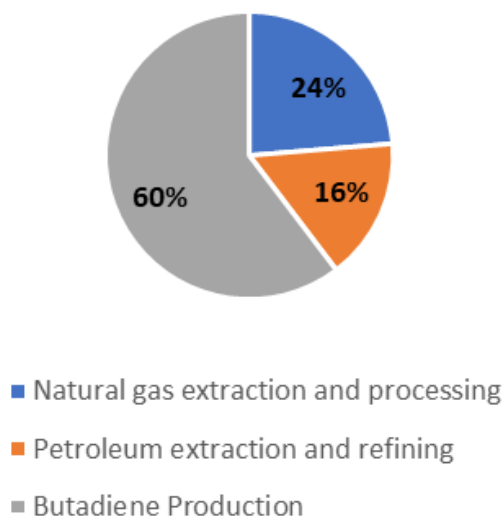
Figure 20. Global Warming Potential for Butadiene

ACIDIFICATION POTENTIAL

Acidification assesses the potential of emissions to contribute to the formation and deposit of acid rain on soil and water, which can cause serious harm to plant and animal life as well as effects to infrastructure.[17] Acidification potential modeling in TRACI incorporates the results of an atmospheric chemistry and transport model, developed by the U.S. National Acid Precipitation Assessment Program (NAPAP), to estimate total North American terrestrial deposition due to atmospheric emissions of NO_x and SO_2, as a function of the emissions location.[18,19]

Acidification impacts are typically dominated by fossil fuel combustion emissions, particularly sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Emissions from combustion of fossil fuels, especially coal, to generate grid electricity is a significant contributor to acidification impacts for all systems.

Table 22 shows total acidification potential (AP) results for the ethylene production system. Results are shown graphically in Figure 21. The ethylene production comprises 30 percent of the total AP, although only 6 percent of this amount are from process emissions, with the

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[17]   Bare, J. C. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User's Manual; EPA/600/R-12/554 2012.
[18]   Bare JC, Norris GA, Pennington DW, McKone T. (2003). TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, *Journal of Industrial Ecology,* **6**(3–4): 49–78. Available at URL: http://mitpress.mit.edu/journals/pdf/jiec_6_3_49_0.pdf.
[19]   Bare JC. (2002). Developing a consistent decision-making framework by using the US EPA's TRACI, AICHE. Available at URL: http://www.epa.gov/nrmrl/std/sab/traci/aiche2002paper.pdf.

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remaining from the production and combustion of fuels used at the plant. The extraction and processing of natural gas used to create 90 percent of the material inputs to the ethylene plants produces 66 percent of the total emissions impacting AP. The remaining 4 percent of the AP results come from the extraction and refining of petroleum used to create 10 percent of the ethylene material inputs. The transport of materials in the ethylene system account for only 1 percent of the AP results.

Table 22. Acidification Potential for Ethylene

	Acidification Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb SO2 eq	*kg SO2 eq*	*%*
Natural gas extraction and processing	2.55	2.55	65.8%
Petroleum extraction and refining	0.16	0.16	4.2%
Ethylene Production	1.16	1.16	29.9%
Total	**3.87**	**3.87**	**100%**
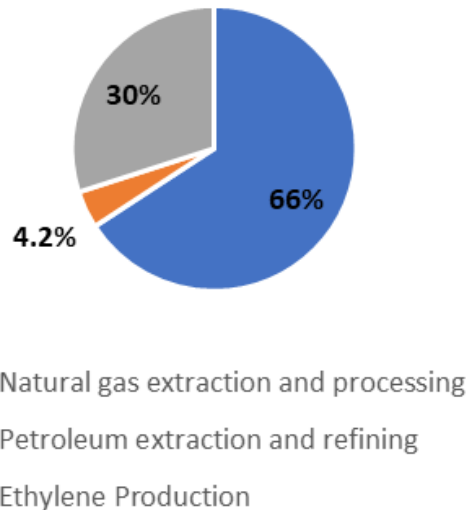
Figure 21. Acidification Potential for Ethylene

Table 23 shows total AP results for the propylene production system. Results are shown graphically in Figure 22. The propylene production comprises over 30 percent of the total AP, although almost 6 percent of this amount are from process and flare emissions, with the remaining from the production and combustion of fuels used at the plant. The extraction and processing of natural gas used to create 86 percent of the material inputs to the propylene plants produces 63 percent of the total emissions impacting AP. Almost 6 percent of the AP results come from the extraction and refining of petroleum used to create 14 percent of the propylene material inputs.

Table 23. Acidification Potential for Propylene

	Acidification Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb SO2 eq	*kg SO2 eq*	*%*
Natural gas extraction and processing	2.47	2.47	63.4%
Petroleum extraction and refining	0.23	0.23	5.9%
Propylene Production	1.19	1.19	30.6%
Total	3.89	3.89	100%
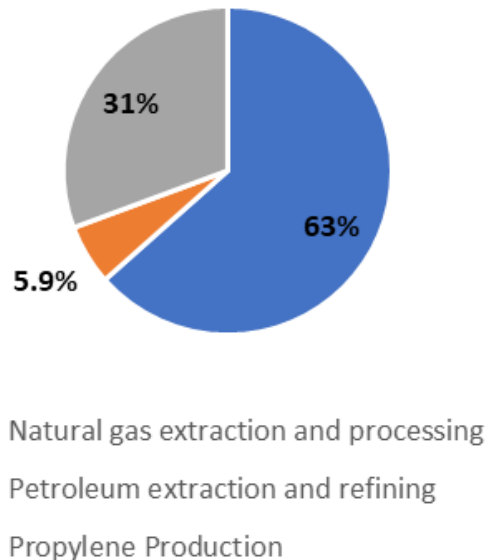
Figure 22. Acidification Potential for Propylene

Table 24 shows total AP results for the Pyrolysis gasoline production system. Results are shown graphically in Figure 23. The pygas manufacturing process produces almost 31 percent of the total AP, although only 6 percent of this amount are from process emissions, with the remaining from the production and combustion of fuels used at the plant. The extraction and processing of natural gas used to create 89 percent of the material inputs to the pygas plants produces 65 percent of the total emissions impacting AP. The remaining 4 percent of the AP results come from the extraction and refining of petroleum used to create 11 percent of the pygas material inputs.

Table 24. Acidification Potential for Pyrolysis Gasoline

	Acidification Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb SO2 eq	kg SO2 eq	%
Natural gas extraction and processing	2.52	2.52	64.7%
Petroleum extraction and refining	0.18	0.18	4.6%
Pyrolysis gasoline Production	1.20	1.20	30.7%
Total	3.90	3.90	100%
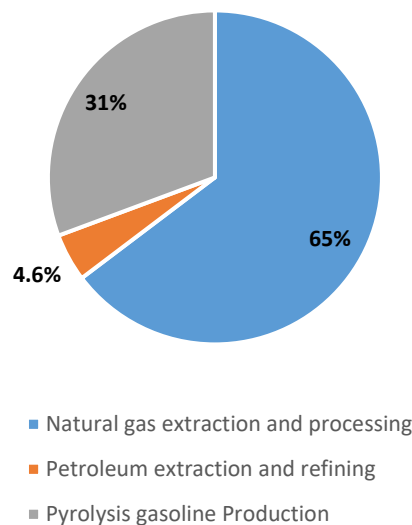
Figure 23. Acidification Potential for Pyrolysis Gasoline

Table 25 shows total AP results for the butadiene production system, while the results are shown graphically in Figure 24. The butadiene manufacturing process produces approximately 20 percent of the total AP, with about 6 percent of this amount from process emissions, and the remaining from the production and combustion of fuels used at the plant. The extraction and processing of natural gas used to create 77 percent of the material inputs to the butadiene plants produces 68 percent of the total emissions impacting AP. The remaining almost 12 percent of the AP results come from the extraction and refining of petroleum used to create 23 percent of the butadiene material inputs.

Table 25. Acidification Potential for Butadiene

	Acidification Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb SO2 eq	*kg SO2 eq*	*%*
Natural gas extraction and processing	2.30	2.30	68.3%
Petroleum extraction and refining	0.39	0.39	11.7%
Butadiene Production	0.67	0.67	20.0%
Total	**3.36**	**3.36**	**100%**
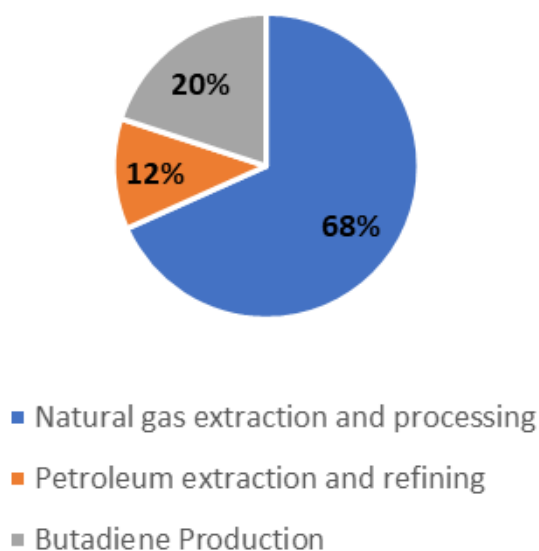
Figure 24. Acidification Potential for Butadiene

EUTROPHICATION POTENTIAL

Eutrophication occurs when excess nutrients (nitrates, phosphates) are introduced to surface water causing the rapid growth of aquatic plants. Excess releases of these substances may provide undesired effects on the waterways.[20] The TRACI characterization factors for eutrophication are the product of a nutrient factor and a transport factor.[21] The nutrient factor is based on the amount of plant growth caused by each pollutant, while the transport

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[20]   Bare, J. C. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User's Manual; EPA/600/R-12/554 2012.

[21]   Bare JC, Norris GA, Pennington DW, McKone T. (2003). TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, *Journal of Industrial Ecology,* **6**(3–4): 49–78. Available at URL: http://mitpress.mit.edu/journals/pdf/jiec_6_3_49_0.pdf.

factor accounts for the probability that the pollutant will reach a body of water. Atmospheric emissions of nitrogen oxides (NO_x) as well as waterborne emissions of nitrogen, phosphorus, ammonia, biochemical oxygen demand (BOD), and chemical oxygen demand (COD) are the main contributors to eutrophication impacts.

Eutrophication potential (EP) results for ethylene are shown in

Table 26 and illustrated in Figure 25. The largest portion, 61 percent, of the EP results come from natural gas extraction and processing used to create 90 percent of the incoming materials at the ethylene plant. The ethylene production creates 35 percent of the EP impact, with 15 percent of that representing the process and flare emissions at the plant, and the rest for the production and combustion of fuels used during transport of incoming materials or at the plant. The final 4 percent of the total EP are from the petroleum extraction and refining used to create 10 percent of the incoming materials to the ethylene plant.

Table 26. Eutrophication Potential for Ethylene

	Eutrophication Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb N eq	*kg N eq*	*%*
Natural gas extraction and processing	0.14	0.14	60.8%
Petroleum extraction and refining	0.009	0.009	3.9%
Ethylene Production	0.082	0.082	35.3%
Total	**0.23**	**0.23**	**100%**
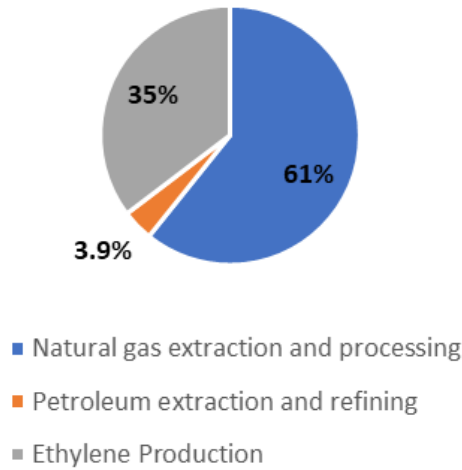
Figure 25. Eutrophication Potential for Ethylene

Eutrophication potential (EP) results for propylene are shown in

Table **27** and illustrated in Figure 26. Fifty-eight percent of the EP results come from natural gas extraction and processing used to create 86 percent of the incoming materials at the propylene plant. The propylene production creates almost 37 percent of the EP impact, with almost 16 percent representing the process and flare emissions at the plant, and the rest for the production and combustion of fuels used during transport of incoming materials or at the plant. The final 5 percent of the total EP are from the petroleum extraction and refining used to create 14 percent of the incoming materials to the propylene plant.

Table 27. Eutrophication Potential for Propylene

	Eutrophication Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb N eq	*kg N eq*	*%*
Natural gas extraction and processing	0.14	0.14	57.9%
Petroleum extraction and refining	0.013	0.013	5.4%
Propylene Production	0.086	0.086	36.7%
Total	**0.23**	**0.23**	**100%**

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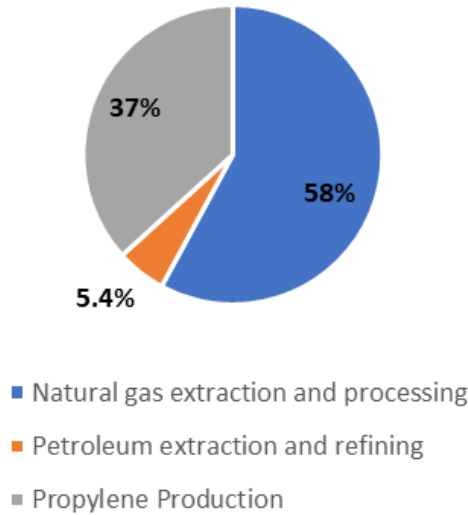
Figure 26. Eutrophication Potential for Propylene

Eutrophication potential (EP) results for pyrolysis gasoline are shown in
Table 28 and illustrated in Figure 27. Almost 60 percent, of the EP results come from natural gas extraction and processing used to create 89 percent of the incoming materials at the pygas plant. The pygas production creates 36 percent of the EP impact, with 14 percent representing the process and flare emissions at the plant, and the rest for the production and combustion of fuels used during transport of incoming materials or at the plant. The final 4 percent of the total EP are from the petroleum extraction and refining used to create 11 percent of the incoming materials to the pygas plant.

Table 28. Eutrophication Potential for Pyrolysis Gasoline

	Eutrophication Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb N eq	*kg N eq*	*%*
Natural gas extraction and processing	0.14	0.14	59.9%
Petroleum extraction and refining	0.010	0.010	4.3%
Pyrolysis gasoline Production	0.08	0.08	35.9%
Total	**0.23**	**0.23**	**100%**
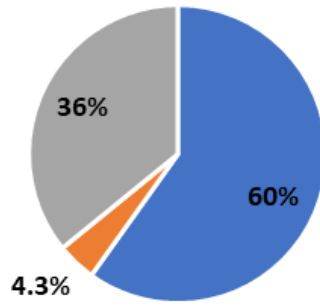
Figure 27. Eutrophication Potential for Pyrolysis Gasoline

Eutrophication potential (EP) results for butadiene are shown in Table 29 and illustrated in Figure 28. Close to 50 percent, of the EP results come from natural gas extraction and processing used to create 77 percent of the incoming materials at the olefins plant. The butadiene production creates over 40 percent of the EP impact, representing the process and flare emissions at the plant, as well as the production and combustion of fuels used during transport of incoming materials or at the plant. Nine percent of the total EP are from the petroleum extraction and refining used to create 23 percent of the incoming materials to the butadiene average plant.

Table 29. Eutrophication Potential for Butadiene

	Eutrophication Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb N eq	*kg N eq*	*%*
Natural gas extraction and processing	0.13	0.13	49.7%
Petroleum extraction and refining	0.022	0.022	8.5%
Butadiene Production	0.11	0.11	41.8%
Total	**0.25**	**0.25**	**100%**
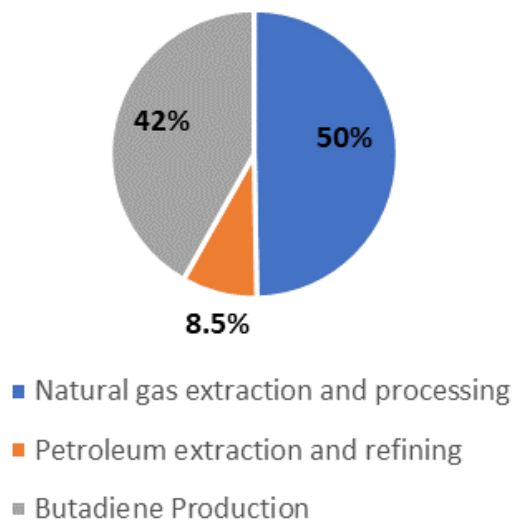
Figure 28. Eutrophication Potential for Butadiene

OZONE DEPLETION POTENTIAL

Stratospheric ozone depletion (ODP) is the reduction of the protective ozone within the stratosphere caused by emissions of ozone-depleting substance (e.g. CFCs and halons). The ozone depletion impact category characterizes the potential to destroy ozone based on a chemical's reactivity and lifetime. Effects related to ozone depletion can include skin cancer, cataracts, material damage, immune system suppression, crop damage, and other plant and animal effects.[22] For the olefins systems, the main sources of emissions contributing to ODP are minute amounts of a few CFCs, HCFCs, and halons are emitted during the extraction of petroleum, which is used as fuel and material in the production of olefins.

Table 30 shows total ODP results for ethylene, which are also shown graphically in Figure 29. Ozone depletion results for the ethylene are dominated by the crude oil extraction and refining system, contributing 85 percent of the total ozone depletion impacts. The remaining ozone depletion impacts are primarily associated with the production of ethylene at 15 percent. The amount of the ODP shown as ethylene production is from the production of fuels used within the plant. No emissions impacting ODP are released at the ethylene plant. The input materials to the ethylene coming from natural gas make up less than 1 percent of the total ODP also due to the use of petroleum fuels within the production of the natural gas.

Table 30. Ozone Depletion Potential for Ethylene

	Ozone Depletion Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CFC-11 eq	*kg CFC-11 eq*	*%*
Natural gas extraction and processing	4.5E-09	4.5E-09	0.4%
Petroleum extraction and refining	1.0E-06	1.0E-06	85.1%
Ethylene Production	1.8E-07	1.8E-07	14.5%
Total	**1.2E-06**	**1.2E-06**	**100%**

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22   Bare, J. C. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User's Manual; EPA/600/R-12/554 2012.
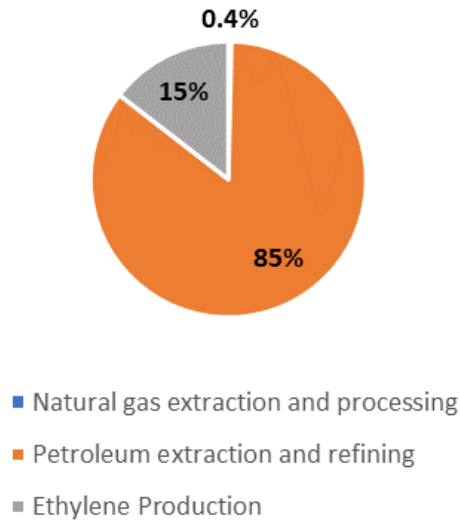
Figure 29. Ozone Depletion Potential for Ethylene

Table 31 shows total ODP results for propylene, which are also shown graphically in Figure 30. Ozone depletion results for the propylene are dominated by the crude oil extraction and refining system, contributing almost 85 percent of the total ozone depletion impacts. The amount is higher than for the ethylene system ODP results due to the increased use of petroleum products as input materials to the propylene system. The remaining ozone depletion impacts are primarily associated with the production of propylene at 15 percent. The amount of the ODP shown as propylene production is from the production of fuels used within the plant. No emissions impacting ODP are released at the propylene plant. The input materials to the propylene coming from natural gas make up less than 1 percent of the total ODP also due to the use of petroleum fuels within the production of the natural gas.

Table 31. Ozone Depletion Potential for Propylene

	Ozone Depletion Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CFC-11 eq	kg CFC-11 eq	%
Natural gas extraction and processing	4.3E-09	4.3E-09	0.3%
Petroleum extraction and refining	1.5E-06	1.5E-06	84.5%
Propylene Production	2.6E-07	2.6E-07	15.3%
Total	1.7E-06	1.7E-06	100%
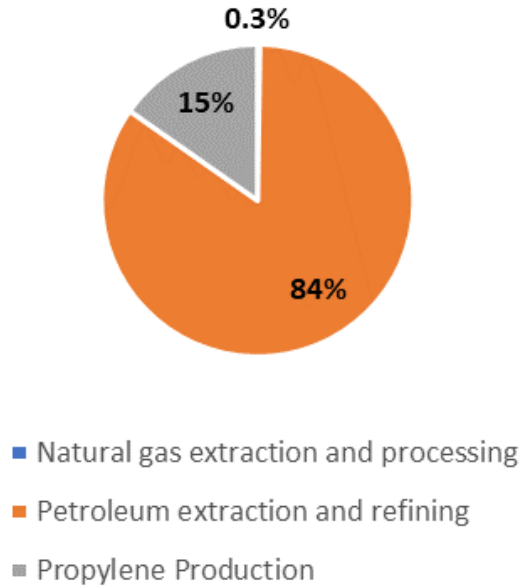
Figure 30. Ozone Depletion Potential for Propylene

Table 32 shows total ODP results for pyrolysis gasoline, which are also shown graphically in Figure 31. Ozone depletion results for the pygas are dominated by the crude oil extraction and refining system, contributing 85 percent of the total ozone depletion impacts. The remaining ozone depletion impacts are primarily associated with the production of pygas at over 14 percent. The amount of the ODP shown as pygas production is from the production of fuels used within the plant. No emissions impacting ODP are released at the pygas plant. The input materials to the pygas coming from natural gas make up less than 1 percent of the total ODP also due to the use of petroleum fuels within the production of the natural gas.

Table 32. Ozone Depletion Potential for Pyrolysis Gasoline

	Ozone Depletion Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CFC-11 eq	*kg CFC-11 eq*	*%*
Natural gas extraction and processing	4.4E-09	4.4E-09	0.3%
Petroleum extraction and refining	1.1E-06	1.1E-06	85.0%
Pyrolysis gasoline Production	2.0E-07	2.0E-07	14.7%
Total	**1.3E-06**	**1.3E-06**	**100%**
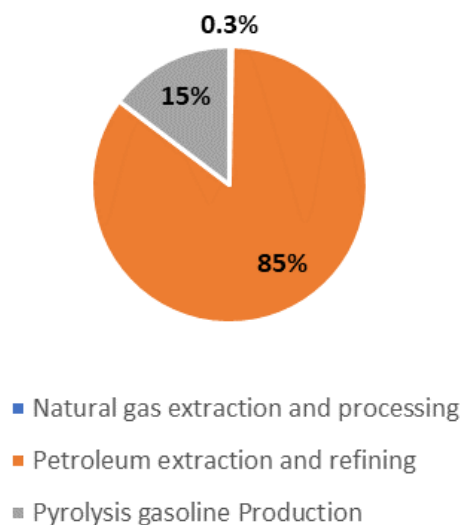
Figure 31. Ozone Depletion Potential for Pyrolysis Gasoline

Table 33 shows total ODP results for butadiene, which are also shown graphically in Figure 32. Ozone depletion results for the butadiene are dominated by the crude oil extraction and refining system, contributing almost 85 percent of the total ozone depletion impacts. The amount is higher than for the other olefin system ODP results due to the increased use of petroleum products as input materials to the butadiene system. The remaining ozone depletion impacts are primarily associated with the production of butadiene at 15 percent. The amount of the ODP shown as butadiene production is from the production of fuels used within the plant. No emissions impacting ODP are released at the butadiene plant. The input materials to the butadiene coming from natural gas make up only 0.1 percent of the total ODP also due to the use of petroleum fuels within the production of the natural gas.

Table 33. Ozone Depletion Potential for Butadiene

	Ozone Depletion Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CFC-11 eq	*kg CFC-11 eq*	*%*
Natural gas extraction and processing	4.0E-09	4.0E-09	0.1%
Petroleum extraction and refining	2.5E-06	2.5E-06	85.0%
Butadiene Production	4.4E-07	4.4E-07	14.9%
Total	**2.9E-06**	**2.9E-06**	**100%**
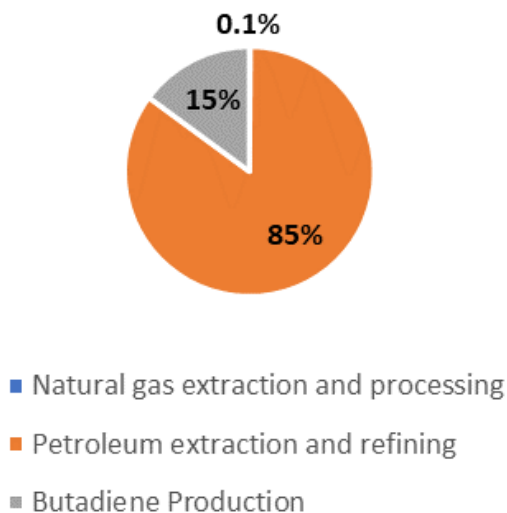
Figure 32. Ozone Depletion Potential for Butadiene

PHOTOCHEMICAL SMOG FORMATION

The photochemical smog formation (POCP) impact category characterizes the potential of airborne emissions to cause photochemical smog. The creation of photochemical smog occurs when sunlight reacts with NO_x and volatile organic compounds (VOCs), resulting in tropospheric (ground-level) ozone and particulate matter. Endpoints of such smog creation can include increased human mortality, asthma, and deleterious effects on plant growth.[23] Smog formation impact are generally dominated by emissions associated with fuel combustion, so that impacts are higher for life cycle stages and components that have higher process fuel and transportation fuel requirements. In this case, NO_x makes up more than 96 percent of the smog formation emissions, with VOCs consisting of another 3 percent. Natural gas extraction and processing are where the largest amounts of these emissions are released and so dominate the POCP category.

Smog formation potential results for ethylene are displayed in Table 34 and illustrated in Figure 33. The largest portion of the POCP impact results come from the natural gas inputs to the ethylene plant, which makes up 66 percent of the total. The production of natural gas used for materials and fuels overall in the ethylene system account for 84 percent of the POCP impact; this includes natural gas used as fuels in the petroleum input materials and ethylene plant. The petroleum products used as incoming materials for the ethylene system create the emissions leading to less than 5 percent of the POCP results.

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[23] Bare, J. C. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User's Manual; EPA/600/R-12/554 2012.

The remaining almost 29 percent of the POCP impact is created from the ethylene production process. Much of this percentage is from the use of natural gas and petroleum products as fuels in the plant. Only 7 percent of the total emissions resulting in the POCP impact are released at the ethylene plant as process emissions.

Table 34. Photochemical Smog Formation Potential for Ethylene

	Photochemical Smog Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb O3 eq	*kg O3 eq*	*%*
Natural gas extraction and processing	74.0	74.0	66.2%
Petroleum extraction and refining	4.95	4.95	4.4%
Ethylene Production	32.8	32.8	29.4%
Total	**112**	**112**	**100%**

- Natural gas extraction and processing
- Petroleum extraction and refining
- Ethylene Production
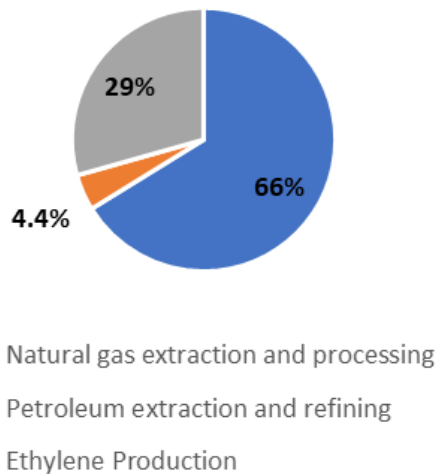
Figure 33. Smog Formation Potential for Ethylene

Smog formation potential results for propylene are displayed in Table 35 and illustrated in Figure 34. The largest portion of the POCP impact results come from the natural gas inputs to the propylene plant, which makes up 64 percent of the total. The production of natural gas used for materials and fuels overall in the propylene system account for 82 percent of the POCP impact; this includes natural gas used as fuels in the petroleum input materials and propylene plant. These percentages are somewhat less than for the ethylene plants due to the use of less natural gas as input materials for those olefins plants producing larger amounts of propylene. The petroleum products used as incoming materials for the propylene system create the emissions leading to more than 6 percent of the POCP impact category.

The remaining 30 percent of the POCP impact is created from the propylene production process. Much of this percentage is from the use of natural gas and petroleum products as fuels in the plant. Seven percent of the total emissions resulting in the POCP impact are released at the propylene plant as process emissions.

Table 35. Photochemical Smog Formation Potential for Propylene

	Photochemical Smog Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb O3 eq	*kg O3 eq*	*%*
Natural gas extraction and processing	71.5	71.5	63.8%
Petroleum extraction and refining	6.93	6.93	6.2%
Propylene Production	33.6	33.6	30.0%
Total	**112**	**112**	**100%**
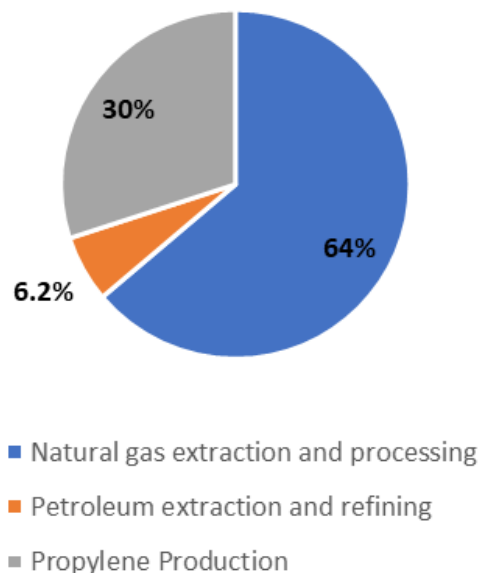
Figure 34. Smog Formation Potential for Propylene

Smog formation potential results for Pyrolysis gasoline are displayed in Table 36 and illustrated in Figure 35. The largest portion of the POCP impact results come from the natural gas inputs to the pygas plant, which makes up 65 percent of the total. The production of natural gas used for materials and fuels overall in the pygas system account for 83 percent of the POCP impact; this includes natural gas used as fuels in the petroleum input materials

and pygas plant. The petroleum products used as incoming materials for the pygas system create the emissions producing 5 percent of the POCP impact category.

The remaining over 30 percent of the POCP impact is created from the pygas production process. Much of this percentage is from the use of natural gas and petroleum products as fuels in the plant. Only 7 percent of the total emissions resulting in the POCP impact are released at the pygas plant as process emissions.

Table 36. Photochemical Smog Formation Potential for Pyrolysis Gasoline

	Photochemical Smog Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb O3 eq	*kg O3 eq*	*%*
Natural gas extraction and processing	73.2	73.2	65.0%
Petroleum extraction and refining	5.44	5.44	4.8%
Pyrolysis gasoline Production	33.9	33.9	30.1%
Total	**112**	**112**	**100%**
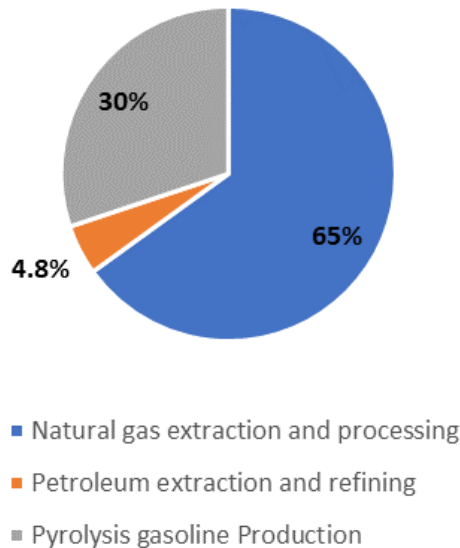
Figure 35. Smog Formation Potential for Pyrolysis Gasoline

Smog formation potential results for Pyrolysis gasoline are displayed in Table 37 and illustrated in Figure 36. The largest portion of the POCP impact results come from the natural gas inputs to the butadiene average plant, which makes up over 70 percent of the total. The production of natural gas used for materials and fuels overall in the butadiene system account for 84 percent of the POCP impact; this includes natural gas used as fuels in the petroleum input materials and butadiene plant. The petroleum products used as incoming materials for the butadiene system create the emissions producing over 12 percent of the POCP impact category. Almost 17 percent of the POCP impact is created from the butadiene production process. Much of this percentage is from the use of natural gas and petroleum products as fuels in the plant with the remaining emissions released at the butadiene plant as process emissions.

Table 37. Photochemical Smog Formation Potential for Butadiene

	Photochemical Smog Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb O3 eq	kg O3 eq	%
Natural gas extraction and processing	66.6	66.6	70.5%
Petroleum extraction and refining	11.9	11.9	12.6%
Butadiene Production	16.0	16.0	16.9%
Total	94.4	94.4	100%
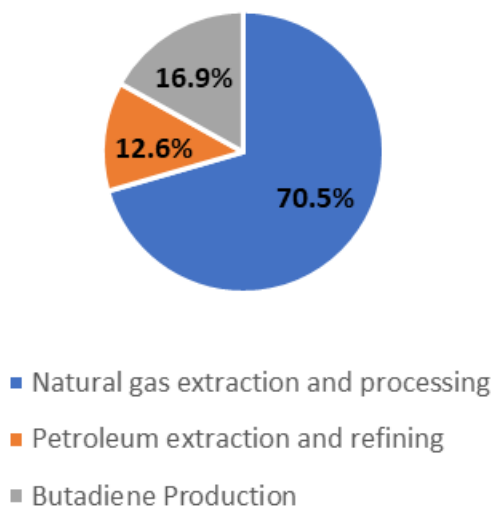
Figure 36. Smog Formation Potential for Butadiene

APPENDIX: OLEFINS MANUFACTURE

This appendix discusses the manufacture of olefins, which are used as an incoming material for most plastics. Olefins included in this report are ethylene, propylene, and pyrolysis gasoline (pygas). The captured ethylene production amount is approximately 10 percent[24] of the ethylene production in the U.S. in 2015. The captured propylene production amount is estimated to be 4 percent[25] of the total propylene production in the U.S. in 2015. The flow diagram of processes included for olefins is provided in Figure 37. Flow diagram for the Production of Olefins. Individual unit process tables on the bases of 1,000 pounds and 1,000 kilograms are also shown within this appendix. The following processes are included in this appendix:

- Crude oil production
- Petroleum refining
- Natural gas production
- Natural gas processing
- Olefins production

LCI data for olefins production were collected for this update to the U.S. LCI plastics database by member companies of the American Chemistry Council (ACC). Secondary data was used for crude oil extraction and refining and natural gas production and processing.
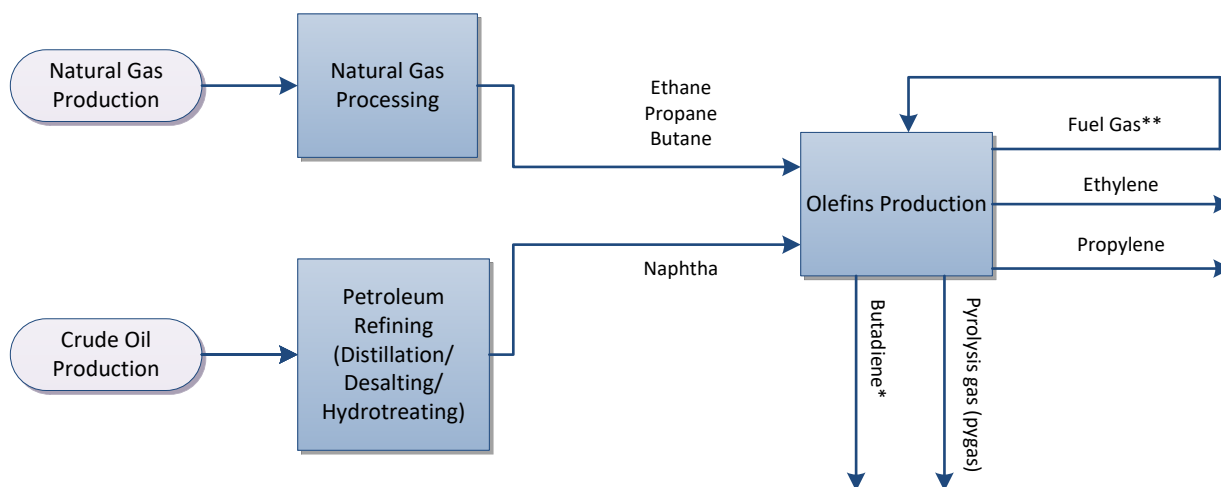
Figure 37. Flow diagram for the Production of Olefins.

*Results for the production of butadiene are included in this report, but unit process data are not shown due to confidentiality.
**Fuel gas used for energy is created from off-gas produced in the process.
Note: Coproduct allocation was given for crude C4's, ethane, hydrogen and acetylene (not shown in the diagram) using mass allocation. Additional coproducts include some fuels created in the process, which are given an energy allocation.

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[24] Oil and Gas Journal, 2017. US olefins industry prepares for waves of new capacity. March 6, 2017. Vol. 115, Issue 3. Calculations performed by Franklin Associates.
[25] Ibid.

CRUDE OIL EXTRACTION

Oil is produced by drilling into porous rock structures generally located several thousand feet underground. Once an oil deposit is located, numerous holes are drilled and lined with steel casing. Some oil is brought to the surface by natural pressure in the rock structure, although most oil requires energy to drive pumps that lift oil to the surface. Once oil is on the surface, it is separated from water and stored in tanks before being transported to a refinery. In some cases, it is immediately transferred to a pipeline that transports the oil to a larger terminal.

The U.S. crude oil production is made up of domestic on-shore, domestic off-shore, imported on-shore and imported off-shore sources. Based on the 2014 national average petroleum supply chain, LCI data is calculated using pollutant emission records from the National Emissions Inventory (NEI), domestic petroleum production data, and imported oil data. Table 38 provides the percentages for each type of crude oil extraction source as used for this unit process data set.

Table 38. Percentage Contribution by Source to Crude Oil Extraction Mix

Domestic Onshore	Domestic Offshore	Foreign Onshore	Foreign Offshore
42.36%	8.75%	38.55%	10.33%

Sources: US EPA 2017, US Energy Information Administration (EIA) 2017a, Sheridan 2006, National Oceanic and Atmospheric Administration (NOAA) 2017, Bureau of Ocean Energy Management (BOEM) 2017, US EIA 2017b, US EIA 2017c

The data for this unit process provides a summary of relevant input and output flows associated with extraction of domestic and imported crude oil and condensate. The data set takes into account domestic onshore extraction, domestic offshore extraction, foreign onshore extraction, and foreign offshore extraction based on the percentages provided in Table 38. The energy inputs of this process are taken from GREET model 2017 (ANL, 2017). These inputs include energy from natural gas, petroleum and other fossil fuels in addition to electricity use. The energy inputs are assumed to be the same for the domestic and imported on-shore and off-shore extraction processes. Table 39 shows the energy requirements for the extraction of 1,000 pounds and 1,000 kilograms of crude oil as per the GREET 2017 model.

The emission data for the process is adapted from inventory data compiled by the National Energy Technology Lab. The following briefly summarizes that data collection effort as documented in Young et. al. 2019. The inventory for crude oil extraction accounts for emissions to air as reported in the NEI for U.S. extraction sites, greenhouse gas emissions from Cooney et. al. 2017, and emissions to water from EPA's Discharge Monitoring Reports. Non-greenhouse gas (GHG) emissions inventories for foreign oil extraction are unavailable so were assumed to scale linearly according to changes in carbon dioxide emission from domestic extraction. Emissions data from each U.S. county were allocated between oil

extraction and natural gas based on North American Industry Classification System (NAICS) and source classification codes included in the NEI. For cases in which not enough detail was provided from emissions records, emissions were allocated between oil and gas in that county based on the energy content of reported production.

Table 39. Energy Requirements for the Extraction of Crude Oil

	1,000 lb	1,000 kg
Energy		
Process Energy		
Electricity from grid	16.4 kWh	36.3 kWh
Natural gas	0.28 ft^3	0.018 m^3
Gasoline	0.063 gal	5.3E-04 m^3
Diesel	0.44 gal	0.0037 m^3
Residual Oil	0.027 gal	2.2E-04 m^3
Distillate Oil	0.027 gal	2.2E-04 m^3

Sources: ANL, 2017

Solid wastes include drilling wastes and associated wastes as calculated from statistics in EPA 2000 and API 2000. Drilling wastes include solids from brine water and drilling mud, while associated wastes are tank bottoms, contaminated soil and scale or sludges from radioactive materials.

No information was found pertaining to fresh water consumption used in onshore or offshore extraction, and so this is not included. Water is extracted with the oil and is called produced water. This produced water is a brine and so not included as consumed water.

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Table 40 through Table 43 provide the emissions for 1,000 pounds and 1,000 kilograms of crude oil extraction by source (onshore domestic, offshore domestic, onshore foreign, and offshore foreign).

Table 40. Environmental Emissions for the Extraction of Crude Oil (Onshore Domestic)

	1,000 lb	1,000 kg
Environmental Emissions		
Atmospheric Emissions		
Carbon dioxide	343 lb	343 kg
Benzene, ethyl-	0.00 lb	0.00 kg
Styrene	0.000 lb	0.000 kg
Benzene, 1,4-dichloro-	0.00 lb	0.00 kg
Ethane, 1,2-dibromo-	1.0E-05 lb	1.0E-05 kg
Butadiene	3.7E-04 lb	3.7E-04 kg
Acrolein	0.0018 lb	0.0018 kg
Ethane, 1,2-dichloro-	4.7E-07 lb	4.7E-07 kg
Ethylene glycol	2.0E-08 lb	2.0E-08 kg
4-Methyl-2-pentanone	2.5E-06 lb	2.5E-06 kg
m-Xylene	3.8E-07 lb	3.8E-07 kg
Toluene	0.015 lb	0.015 kg
Benzene, chloro-	8.5E-06 lb	8.5E-06 kg
Phenol	4.5E-06 lb	4.5E-06 kg
Ethanol, 2-methoxy-	2.3E-07 lb	2.3E-07 kg
Hexane	0.0019 lb	0.0019 kg
Ethanol, 2-ethoxy-	7.1E-12 lb	7.1E-12 kg
Diethanolamine	9.5E-08 lb	9.5E-08 kg
Anthracene	3.0E-09 lb	3.0E-09 kg
1,4-Dioxane	1.0E-07 lb	1.0E-07 kg
Ethene, tetrachloro-	2.5E-06 lb	2.5E-06 kg
Pyrene	7.2E-09 lb	7.2E-09 kg
Hydrocarbons, aromatic	3.8E-06 lb	3.8E-06 kg
Cresol	1.2E-09 lb	1.2E-09 kg
Xylene	0.0038 lb	0.0038 kg
Chromium III	7.3E-07 lb	7.3E-07 kg
t-Butyl methyl ether	8.4E-11 lb	8.4E-11 kg
Glycol ethers	2.2E-08 lb	2.2E-08 kg
Arsenic, ion	1.2E-06 lb	1.2E-06 kg
Chromium VI	3.4E-07 lb	3.4E-07 kg
Benzo(g,h,i)perylene	1.7E-06 lb	1.7E-06 kg
Benzo(e)pyrene	1.3E-09 lb	1.3E-09 kg
Indeno(1,2,3-cd)pyrene	2.0E-10 lb	2.0E-10 kg
Perylene	1.5E-11 lb	1.5E-11 kg
Benzo(b)fluoranthene	8.4E-10 lb	8.4E-10 kg
Fluoranthene	7.4E-09 lb	7.4E-09 kg
Benzo(k)fluoranthene	1.5E-10 lb	1.5E-10 kg
Acenaphthylene	2.7E-08 lb	2.7E-08 kg
Chrysene	4.7E-09 lb	4.7E-09 kg
Hydrazine	3.9E-15 lb	3.9E-15 kg
Cyanamide	1.3E-09 lb	1.3E-09 kg
Carbonyl sulfide	1.2E-04 lb	1.2E-04 kg

Table 40. Environmental Emissions for the Extraction of Crude Oil (Onshore Domestic) (continued)

Environmental Emissions	1,000 lb		1,000 kg	
Atmospheric Emissions **				
Formaldehyde	0.017	lb	0.017	kg
Benzo(a)pyrene	1.6E-09	lb	1.6E-09	kg
Dibenz(a,h)anthracene	2.1E-10	lb	2.1E-10	kg
Pentane, 2,2,4-trimethyl-	1.6E-04	lb	1.6E-04	kg
Propene, 1,3-dichloro-	6.7E-06	lb	6.7E-06	kg
Methane, tetrachloro-, CFC-10	8.7E-06	lb	8.7E-06	kg
3-Methylcholanthrene	5.9E-11	lb	5.9E-11	kg
Benzo(a)anthracene	1.7E-07	lb	1.7E-07	kg
7,12-Dimethylbenz(a)anthracene	5.2E-10	lb	5.2E-10	kg
Carbon monoxide	0.63	lb	0.63	kg
Methanol	0.0020	lb	0.0020	kg
Chloroform	7.2E-06	lb	7.2E-06	kg
Benzene	0.024	lb	0.024	kg
Ethane, 1,1,1-trichloro-, HCFC-140	1.3E-05	lb	1.3E-05	kg
Lead	3.9E-06	lb	3.9E-06	kg
Manganese	4.7E-07	lb	4.7E-07	kg
Mercury	9.4E-08	lb	9.4E-08	kg
Nickel	4.3E-06	lb	4.3E-06	kg
Beryllium	3.7E-08	lb	3.7E-08	kg
Cadmium	1.3E-07	lb	1.3E-07	kg
Cobalt	4.7E-09	lb	4.7E-09	kg
Sulfur dioxide	0.082	lb	0.082	kg
Methane, bromo-, Halon 1001	1.1E-12	lb	1.1E-12	kg
Methane, monochloro-, R-40	4.2E-11	lb	4.2E-11	kg
Ethane, chloro-	8.0E-08	lb	8.0E-08	kg
Ethene, chloro-	4.4E-06	lb	4.4E-06	kg
Acetaldehyde	0.0021	lb	0.0021	kg
Methane, dichloro-, HCC-30	2.5E-05	lb	2.5E-05	kg
Carbon disulfide	6.4E-07	lb	6.4E-07	kg
Ethylene oxide	5.3E-11	lb	5.3E-11	kg
Ethane, 1,1-dichloro-	5.9E-06	lb	5.9E-06	kg
Ethene, 1,1-dichloro-	1.2E-09	lb	1.2E-09	kg
Propylene oxide	3.2E-07	lb	3.2E-07	kg
Hydrogen chloride	5.3E-07	lb	5.3E-07	kg
Ammonia	2.7E-04	lb	2.7E-04	kg
Phosphorus	8.7E-07	lb	8.7E-07	kg
Selenium	1.7E-07	lb	1.7E-07	kg
Chlorine	1.8E-07	lb	1.8E-07	kg
Hydrogen sulfide	4.3E-04	lb	4.3E-04	kg
Propane, 1,2-dichloro-	6.8E-06	lb	6.8E-06	kg
Ethane, 1,1,2-trichloro-	8.0E-06	lb	8.0E-06	kg
Ethene, trichloro-	4.8E-08	lb	4.8E-08	kg

Table 40. Environmental Emissions for the Extraction of Crude Oil (Onshore Domestic) (continued)

Environmental Emissions	1,000 lb	1,000 kg
Atmospheric Emissions		
Acrylamide	3.3E-11 lb	3.3E-11 kg
Ethane, 1,1,2,2-tetrachloro-	1.4E-05 lb	1.4E-05 kg
Acenaphthene	9.1E-09 lb	9.1E-09 kg
Phenanthrene	5.2E-08 lb	5.2E-08 kg
Fluorene	2.7E-08 lb	2.7E-08 kg
Naphthalene	5.4E-05 lb	5.4E-05 kg
Naphthalene, 2-methyl-	1.7E-07 lb	1.7E-07 kg
Biphenyl	9.1E-06 lb	9.1E-06 kg
o-Xylene	7.8E-08 lb	7.8E-08 kg
Cumene	1.5E-08 lb	1.5E-08 kg
Acetophenone	8.8E-10 lb	8.8E-10 kg
Nitrogen oxides	0.45 lb	0.45 kg
Particulates, > 2.5 um, and < 10um	3.2E-04 lb	3.2E-04 kg
Particulates, < 2.5 um	0.013 lb	0.013 kg
VOC, volatile organic compounds	4.37 lb	4.37 kg
Waterborne Releases		
Dissolved solids	0.027 lb	0.027 kg
Suspended solids, unspecified	0.0067 lb	0.0067 kg
Sulfate	0.010 lb	0.010 kg
Chloride	0.0016 lb	0.0016 kg
Hydrocarbons, aromatic	1.9E-04 lb	1.9E-04 kg
Ammonia	4.8E-05 lb	4.8E-05 kg
Manganese	3.5E-05 lb	3.5E-05 kg
Oils, unspecified	3.3E-05 lb	3.3E-05 kg
Fluoride	4.3E-06 lb	4.3E-06 kg
Bromide	2.1E-07 lb	2.1E-07 kg
Copper	5.6E-08 lb	5.6E-08 kg
Chlorine	6.5E-10 lb	6.5E-10 kg
Zinc	1.9E-08 lb	1.9E-08 kg
Benzene, ethyl-	7.6E-10 lb	7.6E-10 kg
Mercury	8.3E-11 lb	8.3E-11 kg
Radium-226	3.9E-21 Cu	1.5E-13 kBq
Sulfide	7.2E-05 lb	7.2E-05 kg
Toluene	5.2E-09 lb	5.2E-09 kg
Xylene	6.4E-09 lb	6.4E-09 kg
Solid Wastes		
Solid waste, process to landfill	24.7 lb	24.7 kg

Sources: Young, et. al. 2019, US EPA 2017a, US EPA 2015a, US EPA 2017b, API 2002, US EPA 2000

Table 41. Environmental Emissions for the Extraction of Crude Oil (Offshore Domestic)

	1,000 lb		1,000 kg	
Environmental Emissions				
Atmospheric Emissions				
Carbon dioxide	204	lb	204	kg
Carbon monoxide	0.61	lb	0.61	kg
Sulfur dioxide	0.027	lb	0.027	kg
Nitrogen oxides	0.71	lb	0.71	kg
Particulates, > 2.5 um, and < 10um	1.6E-05	lb	1.6E-05	kg
Particulates, < 2.5 um	0.0070	lb	0.0070	kg
VOC, volatile organic compounds	0.18	lb	0.18	kg
Waterborne Releases				
Chlorine	2.1E-07	lb	2.1E-07	kg
Solid Wastes				
Solid waste, process to landfill	24.7	lb	24.7	kg

Sources: Young, et. al. 2019, BOEM 2017, Cooney, et.al. 2017, US EPA 2015a, API 2002, US EPA 2000

Table 42. Environmental Emissions for the Extraction of Crude Oil (Onshore Foreign)

	1,000 lb		1,000 kg	
Environmental Emissions				
Atmospheric Emissions				
Carbon dioxide	438	lb	438	kg
Benzene, ethyl-	0.0023	lb	0.0023	kg
Styrene	1.5E-05	lb	1.5E-05	kg
Benzene, 1,4-dichloro-	2.2E-06	lb	2.2E-06	kg
Ethane, 1,2-dibromo-	1.3E-05	lb	1.3E-05	kg
Butadiene	4.7E-04	lb	4.7E-04	kg
Acrolein	0.0023	lb	0.0023	kg
Ethane, 1,2-dichloro-	6.0E-07	lb	6.0E-07	kg
Ethylene glycol	2.5E-08	lb	2.5E-08	kg
4-Methyl-2-pentanone	3.2E-06	lb	3.2E-06	kg
m-Xylene	4.8E-07	lb	4.8E-07	kg
Toluene	0.019	lb	0.019	kg
Benzene, chloro-	1.1E-05	lb	1.1E-05	kg
Phenol	5.8E-06	lb	5.8E-06	kg
Ethanol, 2-methoxy-	3.0E-07	lb	3.0E-07	kg
Hexane	0.0024	lb	0.0024	kg
Ethanol, 2-ethoxy-	9.0E-12	lb	9.0E-12	kg
Diethanolamine	1.2E-07	lb	1.2E-07	kg
Anthracene	3.8E-09	lb	3.8E-09	kg
1,4-Dioxane	1.3E-07	lb	1.3E-07	kg
Ethene, tetrachloro-	3.2E-06	lb	3.2E-06	kg
Pyrene	9.2E-09	lb	9.2E-09	kg
Hydrocarbons, aromatic	4.8E-06	lb	4.8E-06	kg
Cresol	1.6E-09	lb	1.6E-09	kg
Xylene	0.0049	lb	0.0049	kg
Chromium III	9.4E-07	lb	9.4E-07	kg
t-Butyl methyl ether	1.1E-10	lb	1.1E-10	kg
Glycol ethers	2.8E-08	lb	2.8E-08	kg
Arsenic, ion	1.6E-06	lb	1.6E-06	kg
Chromium VI	4.4E-07	lb	4.4E-07	kg
Benzo(g,h,i)perylene	2.1E-06	lb	2.1E-06	kg
Benzo(e)pyrene	1.6E-09	lb	1.6E-09	kg
Indeno(1,2,3-cd)pyrene	2.6E-10	lb	2.6E-10	kg
Perylene	1.9E-11	lb	1.9E-11	kg
Benzo(b)fluoranthene	1.1E-09	lb	1.1E-09	kg
Fluoranthene	9.5E-09	lb	9.5E-09	kg
Benzo(k)fluoranthene	1.9E-10	lb	1.9E-10	kg
Acenaphthylene	3.5E-08	lb	3.5E-08	kg
Chrysene	6.1E-09	lb	6.1E-09	kg
Hydrazine	5.0E-15	lb	5.0E-15	kg
Cyanamide	1.6E-09	lb	1.6E-09	kg
Carbonyl sulfide	1.6E-04	lb	1.6E-04	kg

Table 42. Environmental Emissions for the Extraction of Crude Oil (Onshore Foreign) (continued)

Environmental Emissions	1,000 lb		1,000 kg	
Atmospheric Emissions				
Formaldehyde	0.022	lb	0.022	kg
Benzo(a)pyrene	2.0E-09	lb	2.0E-09	kg
Dibenz(a,h)anthracene	2.7E-10	lb	2.7E-10	kg
Pentane, 2,2,4-trimethyl-	2.1E-04	lb	2.1E-04	kg
Propene, 1,3-dichloro-	8.5E-06	lb	8.5E-06	kg
Methane, tetrachloro-, CFC-10	1.1E-05	lb	1.1E-05	kg
3-Methylcholanthrene	7.6E-11	lb	7.6E-11	kg
Benzo(a)anthracene	2.1E-07	lb	2.1E-07	kg
7,12-Dimethylbenz(a)anthracene	6.7E-10	lb	6.7E-10	kg
Carbon monoxide	0.81	lb	0.81	kg
Methanol	0.0026	lb	0.0026	kg
Chloroform	9.3E-06	lb	9.3E-06	kg
Benzene	0.031	lb	0.031	kg
Ethane, 1,1,1-trichloro-, HCFC-140	1.6E-05	lb	1.6E-05	kg
Lead	5.0E-06	lb	5.0E-06	kg
Manganese	6.1E-07	lb	6.1E-07	kg
Mercury	1.2E-07	lb	1.2E-07	kg
Nickel	5.5E-06	lb	5.5E-06	kg
Beryllium	4.7E-08	lb	4.7E-08	kg
Cadmium	1.7E-07	lb	1.7E-07	kg
Cobalt	6.1E-09	lb	6.1E-09	kg
Sulfur dioxide	0.10	lb	0.10	kg
Methane, bromo-, Halon 1001	1.4E-12	lb	1.4E-12	kg
Methane, monochloro-, R-40	5.4E-11	lb	5.4E-11	kg
Ethane, chloro-	1.0E-07	lb	1.0E-07	kg
Ethene, chloro-	5.6E-06	lb	5.6E-06	kg
Acetaldehyde	0.0026	lb	0.0026	kg
Methane, dichloro-, HCC-30	3.1E-05	lb	3.1E-05	kg
Carbon disulfide	8.2E-07	lb	8.2E-07	kg
Ethylene oxide	6.8E-11	lb	6.8E-11	kg
Ethane, 1,1-dichloro-	7.6E-06	lb	7.6E-06	kg
Ethene, 1,1-dichloro-	1.6E-09	lb	1.6E-09	kg
Propylene oxide	4.1E-07	lb	4.1E-07	kg
Hydrogen chloride	6.8E-07	lb	6.8E-07	kg
Ammonia	3.4E-04	lb	3.4E-04	kg
Phosphorus	1.1E-06	lb	1.1E-06	kg
Selenium	2.2E-07	lb	2.2E-07	kg
Chlorine	2.3E-07	lb	2.3E-07	kg
Hydrogen sulfide	5.5E-04	lb	5.5E-04	kg
Propane, 1,2-dichloro-	8.7E-06	lb	8.7E-06	kg

Table 42. Environmental Emissions for the Extraction of Crude Oil (Onshore Foreign) (continued)

Environmental Emissions	1,000 lb		1,000 kg	
Atmospheric Emissions				
Ethane, 1,1,2-trichloro-	1.0E-05	lb	1.0E-05	kg
Ethene, trichloro-	6.1E-08	lb	6.1E-08	kg
Acrylamide	4.3E-11	lb	4.3E-11	kg
Ethane, 1,1,2,2-tetrachloro-	1.7E-05	lb	1.7E-05	kg
Acenaphthene	1.2E-08	lb	1.2E-08	kg
Phenanthrene	6.7E-08	lb	6.7E-08	kg
Fluorene	3.4E-08	lb	3.4E-08	kg
Naphthalene	6.9E-05	lb	6.9E-05	kg
Naphthalene, 2-methyl-	2.2E-07	lb	2.2E-07	kg
Biphenyl	1.2E-05	lb	1.2E-05	kg
o-Xylene	1.0E-07	lb	1.0E-07	kg
Cumene	1.9E-08	lb	1.9E-08	kg
Acetophenone	1.1E-09	lb	1.1E-09	kg
Nitrogen oxides	0.58	lb	0.58	kg
Particulates, > 2.5 um, and < 10um	4.1E-04	lb	4.1E-04	kg
Particulates, < 2.5 um	0.017	lb	0.017	kg
VOC, volatile organic compounds	5.59	lb	5.59	kg
Waterborne Releases				
Dissolved solids	0.027	lb	0.027	kg
Suspended solids, unspecified	0.0067	lb	0.0067	kg
Sulfate	0.010	lb	0.010	kg
Chloride	0.0016	lb	0.0016	kg
Hydrocarbons, aromatic	1.9E-04	lb	1.9E-04	kg
Ammonia	4.8E-05	lb	4.8E-05	kg
Manganese	3.5E-05	lb	3.5E-05	kg
Oils, unspecified	3.3E-05	lb	3.3E-05	kg
Fluoride	4.3E-06	lb	4.3E-06	kg
Bromide	2.1E-07	lb	2.1E-07	kg
Copper	5.6E-08	lb	5.6E-08	kg
Chlorine	6.5E-10	lb	6.5E-10	kg
Zinc	1.9E-08	lb	1.9E-08	kg
Benzene, ethyl-	7.6E-10	lb	7.6E-10	kg
Mercury	8.3E-11	lb	8.3E-11	kg
Radium-226	3.9E-21	Cu	1.5E-13	kBq
Sulfide	7.2E-05	lb	7.2E-05	kg
Toluene	5.2E-09	lb	5.2E-09	kg
Xylene	6.4E-09	lb	6.4E-09	kg
Solid Wastes				
Solid waste, process to landfill	24.7	lb	24.7	kg

Sources: Young, et.al. 2019, Cooney, et.al. 2017, US EIA 2017b, Schlanger 2016, US EPA 2015a, API 2002, US EPA 2000

Table 43. Environmental Emissions for the Extraction of Crude Oil (Offshore Foreign)

	1,000 lb		1,000 kg	
Environmental Emissions				
Atmospheric Emissions				
Carbon dioxide	204	lb	204	kg
Carbon monoxide	0.61	lb	0.61	kg
Sulfur dioxide	0.027	lb	0.027	kg
Nitrogen oxides	0.71	lb	0.71	kg
Particulates, > 2.5 um, and < 10um	1.6E-05	lb	1.6E-05	kg
Particulates, < 2.5 um	0.0070	lb	0.0070	kg
VOC, volatile organic compounds	0.18	lb	0.18	kg
Waterborne Releases				
Chlorine	2.1E-07	lb	2.1E-07	kg
Solid Wastes				
Solid waste, process to landfill	24.7	lb	24.7	kg

Sources: Young, et.al. 2019, Cooney, et.al. 2017, US EIA 2017b, Schlanger 2016, US EPA 2015a, API 2002, US EPA 2000

PETROLEUM REFINING

The refining process begins in a distilling column, where liquid oil is heated to a vapor and lifted upward to be distilled again into separate substances. Distilling exploits the characteristic of the chemicals in crude oil to boil at different temperatures, a phenomenon that engineers chart along distillation curves. A distilling column contains a set of trays that allow heated vapors to rise and collect at different levels, separating out the various liquids derived from crude oil. Since the top of the column is cooler than the bottom, the liquids vaporize and rise, then they condense again, collecting onto their respective trays. Butane and other light products rise to the top of the column, while straight-run gasoline, naphtha, kerosene, diesel, and heavy gas oil gather on the trays, leaving straight run residue at the base of the column. Liquids are considered "heavy" or "light" based on their specific gravity, which is determined based on its weight and density compared to that of water.

Because there is more demand for some distilled products like gasoline, refiners have an incentive to convert heavy liquids into lighter liquids. The term cracking comes from the process of breaking up long hydrocarbon molecules into smaller, more useful molecules. The cracking process converts heavy straight run liquids into lighter liquids, such as gasoline. There are multiple versions of the cracking process, and refiners use the process extensively. Cracking is a highly controlled process, so cracking units exist separate from distillation columns. The most common type of cracking is "cat cracking," named for the use of catalysts, substances added to a chemical reaction to speed up the process. The products from the cracking process may then go to a reformer to create gasoline or other fuels. For

this analysis, no further processes are considered beyond the cracker as naphtha is the common refinery feed sent to steam crackers (olefins plants).

The refinery process key inputs include crude petroleum, electricity, and natural gas. Key outputs include refinery products and emissions to air, water, and soil. The emission data for the process is adapted from inventory data compiled by the National Energy Technology Lab. The following briefly summarizes that data collection effort as documented in [Young, et. al, 2019]. Reported emissions from petroleum refineries in 2014 were compiled from EPA datasets including NEI, Discharge Monitoring Report (DMR), Toxic Release Inventory (TRI) and the Greenhouse Gas Reporting Program (GHGRP). Emissions data, representing releases to air, water, and soil covers 153 U.S. refineries. Crude oil consumption was calculated based on reported operating capacities by refinery and reported utilization (US EIA, 2016). Total production of U.S. refining products is reported by the Energy Information Administration (US EIA, 2017a). EIA also reports annual fuel and material consumption by region (US EIA, 2017n, US EIA, 2017o).

Water consumption data was documented in [Wu, M. et. al., 2009]. The amount used here is an average with the range given as 0.55 to 2.75 cubic meters per 1,000 kg of refined oil. The lower amounts are inclined to come from newer refineries.

No new sources were found for solid wastes created at a refinery. The previous source (Oak Ridge, 1996) was used, which provides the solid waste on a basis of crude oil input. The amount of crude oil required to produce 1,000 kg of refined oil was updated in the calculation.

Data for transport distances of crude oil to the refinery are sourced from Young et. al. 2019. EIA reports annual crude imports by country of origin. Travel distances from those countries via ship were estimated with a shipping distance calculator (Sea-Distances.org). Internal domestic transport of crude oil within and between PADDs by transport type is reported by EIA (US EIA 2017k, US EIA 2017l).

Table 44 provides the LCI input and output data for 1,000 pounds and 1,000 kilograms of refined oil.

Table 44. LCI Data for the Refining of Petroleum Products

	1,000 lb		1,000 kg	
Material Inputs				
Hydrogen gas	4.59	lb	4.59	kg
Methyl tert-butyl	0.14	lb	0.14	kg
Ethanol	3.18	lb	3.18	kg
Sulfuric acid	1.39	lb	1.39	kg
Hydrogen fluoride	0.0042	lb	0.0042	kg
Crude oil	954	lb	954	kg
Energy				
Process Energy				
Electricity from grid	24.9	kWh	54.8	kWh
Natural gas	73.5	ft^3	4.59	m^3
Coal	0.018	lb	0.018	kg
Liquid petroleum gas (LPG)	4.05	gal	0.034	m^3
Residual oil	0.0046	gal	3.9E-05	m^3
Transportation Energy				
Barge	4.97	ton·mi	16.0	tonne·km
Ship	962	ton·mi	3,098	tonne·km
Petroleum Pipeline	183	ton·mi	588	tonne·km
Rail	45.0	ton·mi	145	tonne·km
Environmental Emissions				
Atmospheric Emissions				
Carbon monoxide	0.061	lb	0.061	kg
Nitrogen oxides	0.092	lb	0.092	kg
Particulates, > 2.5 um, and < 10um	0.0035	lb	0.0035	kg
Particulates, < 2.5 um	0.022	lb	0.022	kg
Sulfur dioxide	0.039	lb	0.039	kg
VOC, volatile organic compounds	0.070	lb	0.070	kg
Ethane, 1,1,1-trichloro-, HCFC-140	9.1E-07	lb	9.1E-07	kg
Ethane, 1,1,2,2-tetrachloro-	3.1E-08	lb	3.1E-08	kg
Benzidine, 3,3'-dimethoxy-	6.3E-08	lb	6.3E-08	kg
Benzene, 1,2,4-trichloro-	9.1E-09	lb	9.1E-09	kg
Butane, 1,2-epoxy-	1.7E-07	lb	1.7E-07	kg
Benzene, 1,4-dichloro-	2.4E-08	lb	2.4E-08	kg
1,4-Dioxane	1.2E-08	lb	1.2E-08	kg
1-Methylnapthalene	1.7E-07	lb	1.7E-07	kg
Pentane, 2,2,4-trimethyl-	1.8E-04	lb	1.8E-04	kg
Phenol, 2,4,5-trichloro-	9.1E-09	lb	9.1E-09	kg
Phenol, 2,4,6-trichloro-	1.0E-08	lb	1.0E-08	kg
Phenol, 2,4-dinitro-	9.1E-09	lb	9.1E-09	kg

Table 44. LCI Data for the Refining of Petroleum Products (continued)

	1,000 lb		1,000 kg	
Environmental Emissions				
Atmospheric Emissions				
Ethanol, 2-methoxy-	2.5E-07	lb	2.5E-07	kg
Naphthalene, 2-methyl-	2.8E-07	lb	2.8E-07	kg
Propane, 2-nitro-	8.6E-08	lb	8.6E-08	kg
Benzidine, 3,3'-dichloro-	9.1E-09	lb	9.1E-09	kg
Benzidine, 3,3'-dimethyl-	4.4E-08	lb	4.4E-08	kg
3-Methylcholanthrene	2.9E-11	lb	2.9E-11	kg
4,4'-Methylenebisbenzeneamine	2.7E-08	lb	2.7E-08	kg
Phenol, 4-nitro-	9.1E-09	lb	9.1E-09	kg
Phenanthrene	1.0E-08	lb	1.0E-08	kg
Acenaphthene	1.8E-09	lb	1.8E-09	kg
Acenaphthylene	2.6E-09	lb	2.6E-09	kg
Acetaldehyde	2.6E-05	lb	2.6E-05	kg
Acetamide	8.5E-10	lb	8.5E-10	kg
Acetonitrile	7.5E-06	lb	7.5E-06	kg
Acetophenone	6.1E-07	lb	6.1E-07	kg
Acrolein	6.4E-06	lb	6.4E-06	kg
Acrylonitrile	2.0E-08	lb	2.0E-08	kg
Ammonia	0.0033	lb	0.0033	kg
Aniline	9.2E-07	lb	9.2E-07	kg
Anthracene	4.1E-08	lb	4.1E-08	kg
Antimony	6.7E-06	lb	6.7E-06	kg
Arsenic, ion	5.7E-07	lb	5.7E-07	kg
Asbestos	7.5E-10	lb	7.5E-10	kg
Benzo(a)anthracene	6.3E-08	lb	6.3E-08	kg
Benzene	6.4E-04	lb	6.4E-04	kg
Benzene, chloro-	3.5E-07	lb	3.5E-07	kg
Benzene, ethyl-	2.0E-04	lb	2.0E-04	kg
Benzidine	9.7E-08	lb	9.7E-08	kg
Benzo(a)pyrene	1.1E-05	lb	1.1E-05	kg
Benzo(b)fluoranthene	4.4E-09	lb	4.4E-09	kg
Benzo(e)pyrene	5.0E-11	lb	5.0E-11	kg
Benzo(g,h,i)perylene	1.6E-06	lb	1.6E-06	kg
Benzo(k)fluoranthene	1.1E-09	lb	1.1E-09	kg
Benzofluoranthene	5.1E-09	lb	5.1E-09	kg
Beryllium	5.9E-08	lb	5.9E-08	kg
Biphenyl	9.4E-06	lb	9.4E-06	kg
Bis(2-chloroethyl)ether	9.1E-09	lb	9.1E-09	kg
Butadiene	6.1E-05	lb	6.1E-05	kg

Table 44. LCI Data for the Refining of Petroleum Products
(continued)

Environmental Emissions	1,000 lb		1,000 kg	
Atmospheric Emissions				
Cadmium	7.7E-07	lb	7.7E-07	kg
Carbon disulfide	4.0E-05	lb	4.0E-05	kg
Methane, tetrachloro-, CFC-10	4.4E-07	lb	4.4E-07	kg
Carbonyl sulfide	2.0E-04	lb	2.0E-04	kg
Catechol	1.2E-07	lb	1.2E-07	kg
Chlorine	3.9E-05	lb	3.9E-05	kg
Chloroform	5.1E-06	lb	5.1E-06	kg
Naphthalene, beta-chloro-	6.4E-14	lb	6.4E-14	kg
Chromium VI	4.8E-07	lb	4.8E-07	kg
Chromium III	2.8E-06	lb	2.8E-06	kg
Chrysene	9.0E-08	lb	9.0E-08	kg
Tar	1.7E-07	lb	1.7E-07	kg
Cobalt	6.1E-07	lb	6.1E-07	kg
Cresol	2.5E-05	lb	2.5E-05	kg
Cumene	1.1E-04	lb	1.1E-04	kg
Cyanamide	7.0E-04	lb	7.0E-04	kg
Dibenz(a,h)anthracene	1.2E-08	lb	1.2E-08	kg
Benz(a)acridine	7.2E-11	lb	7.2E-11	kg
Benzo(e)pyrene	1.9E-09	lb	1.9E-09	kg
Dibenzofuran	2.8E-08	lb	2.8E-08	kg
Diethanolamine	5.5E-05	lb	5.5E-05	kg
Dimethyl formamide	3.7E-09	lb	3.7E-09	kg
4-Dimethylaminoazobenzene	5.2E-09	lb	5.2E-09	kg
Epichlorohydrin	6.5E-06	lb	6.5E-06	kg
Ethane, 1,1,2-trichloro-	9.2E-09	lb	9.2E-09	kg
Ethane, 1,1-dichloro-	5.0E-09	lb	5.0E-09	kg
Ethane, 1,2-dibromo-	2.7E-06	lb	2.7E-06	kg
Ethane, 1,2-dichloro-	1.1E-06	lb	1.1E-06	kg
Ethene, chloro-	3.8E-09	lb	3.8E-09	kg
Ethene, tetrachloro-	2.4E-05	lb	2.4E-05	kg
Ethylene glycol	1.5E-05	lb	1.5E-05	kg
Fluoranthene	6.9E-07	lb	6.9E-07	kg
Fluorene	1.2E-08	lb	1.2E-08	kg
Formaldehyde	3.5E-04	lb	3.5E-04	kg
Glycol ethers	1.1E-05	lb	1.1E-05	kg
Butadiene, hexachloro-	9.1E-09	lb	9.1E-09	kg
Benzene, hexachloro-	9.1E-09	lb	9.1E-09	kg

Table 44. LCI Data for the Refining of Petroleum Products (continued)

	1,000 lb		1,000 kg	
Environmental Emissions				
Atmospheric Emissions				
Cyclopentadiene, hexachloro-	9.1E-09	lb	9.1E-09	kg
Ethane, hexachloro-	9.1E-09	lb	9.1E-09	kg
Hexane, 1,6-diisocyanato-	5.2E-08	lb	5.2E-08	kg
Hexane	0.0013	lb	0.0013	kg
Hydrazine	4.3E-10	lb	4.3E-10	kg
Hydrocarbons, aromatic	1.2E-05	lb	1.2E-05	kg
Hydrogen chloride	2.4E-04	lb	2.4E-04	kg
Hydrogen cyanide	0.0022	lb	0.0022	kg
Hydrogen fluoride	2.8E-05	lb	2.8E-05	kg
Hydrogen sulfide	7.3E-04	lb	7.3E-04	kg
Indeno(1,2,3-cd)pyrene	1.5E-08	lb	1.5E-08	kg
Isophorone	1.3E-08	lb	1.3E-08	kg
Lead	2.3E-06	lb	2.3E-06	kg
Manganese	5.4E-06	lb	5.4E-06	kg
m-Cresol	3.8E-08	lb	3.8E-08	kg
Mercury	7.9E-07	lb	7.9E-07	kg
Methane, bromo-, Halon 1001	3.7E-06	lb	3.7E-06	kg
Methane, dichloro-, HCC-30	1.8E-05	lb	1.8E-05	kg
Methane, monochloro-, R-40	5.0E-08	lb	5.0E-08	kg
Methanol	5.6E-04	lb	5.6E-04	kg
4-Methyl-2-pentanone	2.0E-04	lb	2.0E-04	kg
4,4'-Diisocyanatodiphenylmethane	8.0E-08	lb	8.0E-08	kg
Ethane, chloro-	1.8E-10	lb	1.8E-10	kg
Diisobutyl ketone	4.0E-06	lb	4.0E-06	kg
Naphthalene	1.4E-04	lb	1.4E-04	kg
Nickel	1.6E-05	lb	1.6E-05	kg
Nickel refinery dust	2.1E-11	lb	2.1E-11	kg
Nitrobenzene	1.7E-07	lb	1.7E-07	kg
N-Nitrosodimethylamine	9.1E-09	lb	9.1E-09	kg
o-Cresol	3.5E-13	lb	3.5E-13	kg
o-Toluidine	1.8E-08	lb	1.8E-08	kg
o-Xylene	6.0E-07	lb	6.0E-07	kg
p-Xylene	4.8E-07	lb	4.8E-07	kg
Phenol, pentachloro-	2.0E-08	lb	2.0E-08	kg
Perylene	5.8E-12	lb	5.8E-12	kg
Phenanthrene	7.5E-06	lb	7.5E-06	kg
Phenol	8.2E-05	lb	8.2E-05	kg
Phosphorus	1.1E-06	lb	1.1E-06	kg
Phthalate, dibutyl-	2.6E-07	lb	2.6E-07	kg

Table 44. LCI Data for the Refining of Petroleum Products
(continued)

Environmental Emissions	1,000 lb		1,000 kg	
Atmospheric Emissions				
Phthalate, dimethyl-	9.1E-09	lb	9.1E-09	kg
Phthalate, dioctyl-	3.4E-07	lb	3.4E-07	kg
Polychlorinated biphenyls	5.7E-12	lb	5.7E-12	kg
p-Phenylenediamine	3.9E-08	lb	3.9E-08	kg
Propanal	9.3E-09	lb	9.3E-09	kg
Propane, 1,2-dichloro-	5.9E-09	lb	5.9E-09	kg
Propene, 1,3-dichloro-	1.2E-08	lb	1.2E-08	kg
Ethanol, 2-propoxy-	4.5E-08	lb	4.5E-08	kg
Propylene oxide	3.4E-08	lb	3.4E-08	kg
Pyrene	9.1E-07	lb	9.1E-07	kg
Quinoline	1.7E-08	lb	1.7E-08	kg
Selenium	5.8E-07	lb	5.8E-07	kg
Styrene	1.3E-05	lb	1.3E-05	kg
t-Butyl methyl ether	3.1E-05	lb	3.1E-05	kg
Toluene	0.0011	lb	0.0011	kg
Toluene, 2,4-dinitro-	9.1E-09	lb	9.1E-09	kg
Ethene, trichloro-	5.2E-06	lb	5.2E-06	kg
Vinyl acetate	8.3E-08	lb	8.3E-08	kg
Xylene	9.0E-04	lb	9.0E-04	kg
Dioxin, 1,2,3,4,6,7,8,9-octachlorodibenzo-p-	2.2E-12	lb	2.2E-12	kg
Dibenzofuran, 1,2,3,4,6,7,8,9-octachloro-	1.6E-12	lb	1.6E-12	kg
Dioxin, 1,2,3,4,6,7,8-heptachlorodibenzo-p-	1.5E-12	lb	1.5E-12	kg
Dibenzofuran, 1,2,3,4,6,7,8-heptachloro-	5.5E-12	lb	5.5E-12	kg
1,2,3,4,7,8,9 Heptachlorodibenzofuran	1.3E-12	lb	1.3E-12	kg
Dioxin, 1,2,3,4,7,8-hexachlorodibenzo-p	3.3E-13	lb	3.3E-13	kg
Dibenzofuran, 1,2,3,4,7,8-hexachloro-	1.9E-12	lb	1.9E-12	kg
1,2,3,6,7,8-Hexachlorodibenzo-p-dioxin	4.9E-13	lb	4.9E-13	kg
Dibenzofuran, 1,2,3,6,7,8-hexachloro-	2.0E-12	lb	2.0E-12	kg
Dioxin, 1,2,3,7,8,9-hexachlorodibenzo-	4.1E-13	lb	4.1E-13	kg
Dibenzofuran, 1,2,3,7,8,9-hexachloro-	1.2E-12	lb	1.2E-12	kg
1,2,3,7,8-Pentachlorodibenzo-p-dioxin	3.2E-13	lb	3.2E-13	kg
Dibenzofuran, 1,2,3,7,8-pentachloro-	1.4E-12	lb	1.4E-12	kg
Benzene, 1,2,4-trimethyl-	2.1E-04	lb	2.1E-04	kg
1-Methyl-2-pyrrolidinone	3.9E-06	lb	3.9E-06	kg
Dibenzofuran, 2,3,4,6,7,8-hexachloro-	1.9E-12	lb	1.9E-12	kg
Dibenzofuran, 2,3,4,7,8-pentachloro-	1.7E-12	lb	1.7E-12	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	4.0E-13	lb	4.0E-13	kg
Dibenzofuran, 2,3,7,8-tetrachloro-	1.2E-12	lb	1.2E-12	kg

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Table 44. LCI Data for the Refining of Petroleum Products
(continued)

Environmental Emissions	1,000 lb		1,000 kg	
Atmospheric Emissions				
Phenol, 2,4-dimethyl-	1.8E-07	lb	1.8E-07	kg
Bisphenol A	5.6E-06	lb	5.6E-06	kg
Barium	4.3E-09	lb	4.3E-09	kg
Barium compounds	1.9E-07	lb	1.9E-07	kg
1-Butanol	7.4E-07	lb	7.4E-07	kg
Copper	2.3E-07	lb	2.3E-07	kg
Copper compounds	1.2E-06	lb	1.2E-06	kg
4-Methyl-2-methoxyphenol	3.1E-08	lb	3.1E-08	kg
Cyclohexane	2.8E-04	lb	2.8E-04	kg
Dicyclopentadiene	1.7E-06	lb	1.7E-06	kg
Ethene	6.1E-04	lb	6.1E-04	kg
Isoprene	4.8E-06	lb	4.8E-06	kg
Methane, chlorodifluoro-, HCFC-22	1.1E-05	lb	1.1E-05	kg
Molybdenum trioxide	1.2E-06	lb	1.2E-06	kg
Glycidol	3.5E-08	lb	3.5E-08	kg
Ozone	3.7E-05	lb	3.7E-05	kg
Propene	0.0010	lb	0.0010	kg
Silver compounds	6.0E-06	lb	6.0E-06	kg
Sulfuric acid	0.0024	lb	0.0024	kg
t-Butyl alcohol	2.0E-07	lb	2.0E-07	kg
Vanadium	1.1E-08	lb	1.1E-08	kg
Vanadium compounds	2.3E-06	lb	2.3E-06	kg
Zinc compounds	2.8E-05	lb	2.8E-05	kg
Carbon dioxide	220	lb	220	kg
Methane	0.036	lb	0.036	kg
Nitrous oxide	0.0019	lb	0.0019	kg
Waterborne emissions				
Dibenzofuran, 1,2,3,4,6,7,8-heptachloro-	4.1E-13	lb	4.1E-13	kg
Dibenzofuran, 1,2,3,4,7,8-hexachloro-	3.3E-13	lb	3.3E-13	kg
1,2,3,6,7,8-Hexachlorodibenzo-p-dioxin	5.1E-14	lb	5.1E-14	kg
Dioxin, 1,2,3,7,8,9-hexachlorodibenzo-	4.8E-14	lb	4.8E-14	kg
1,2,3,7,8-Pentachlorodibenzo-p-dioxin	4.0E-14	lb	4.0E-14	kg
Benzene, 1,2,4-trimethyl-	6.9E-07	lb	6.9E-07	kg
1-Methyl-2-pyrrolidinone	1.5E-08	lb	1.5E-08	kg
Dibenzofuran, 2,3,4,6,7,8-hexachloro-	5.3E-14	lb	5.3E-14	kg
Dibenzofuran, 2,3,4,7,8-pentachloro-	7.7E-14	lb	7.7E-14	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	1.7E-14	lb	1.7E-14	kg
Dibenzofuran, 2,3,7,8-tetrachloro-	3.5E-14	lb	3.5E-14	kg
Phenol, 2,4-dimethyl-	1.5E-07	lb	1.5E-07	kg
Acetonitrile	3.8E-07	lb	3.8E-07	kg

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Table 44. LCI Data for the Refining of Petroleum Products
(continued)

	1,000 lb		1,000 kg	
Environmental Emissions				
Waterborne emissions				
Ammonia	2.0E-04	lb	2.0E-04	kg
Anthracene	6.5E-08	lb	6.5E-08	kg
Antimony compounds	2.2E-06	lb	2.2E-06	kg
Barium compounds	2.9E-06	lb	2.9E-06	kg
Benzene, ethyl-	9.8E-07	lb	9.8E-07	kg
Benzo(g,h,i)perylene	8.8E-08	lb	8.8E-08	kg
Butadiene	5.3E-08	lb	5.3E-08	kg
Cadmium compounds	1.1E-09	lb	1.1E-09	kg
Carbon disulfide	1.1E-06	lb	1.1E-06	kg
Chlorine	2.5E-07	lb	2.5E-07	kg
Chromium	3.5E-07	lb	3.5E-07	kg
Chromium compounds	2.5E-07	lb	2.5E-07	kg
Cobalt compounds	6.7E-07	lb	6.7E-07	kg
Copper	1.4E-07	lb	1.4E-07	kg
Copper compounds	3.9E-07	lb	3.9E-07	kg
Cresol	1.0E-06	lb	1.0E-06	kg
Cumene	4.1E-07	lb	4.1E-07	kg
Cyanamide	4.3E-07	lb	4.3E-07	kg
Cyclohexane	3.7E-07	lb	3.7E-07	kg
Diethanolamine	5.8E-07	lb	5.8E-07	kg
Ethene	3.5E-07	lb	3.5E-07	kg
Ethene, tetrachloro-	7.9E-08	lb	7.9E-08	kg
Ethylene glycol	2.5E-05	lb	2.5E-05	kg
Ethanol, 2-ethoxy-	2.1E-07	lb	2.1E-07	kg
Hexane	7.4E-07	lb	7.4E-07	kg
Hydrogen fluoride	6.0E-09	lb	6.0E-09	kg
Hydrogen sulfide	1.3E-05	lb	1.3E-05	kg
Isoprene	5.4E-07	lb	5.4E-07	kg
Lead	1.6E-08	lb	1.6E-08	kg
Lead compounds	1.1E-06	lb	1.1E-06	kg
Manganese	4.1E-06	lb	4.1E-06	kg
Manganese compounds	9.3E-07	lb	9.3E-07	kg
Mercury	1.4E-09	lb	1.4E-09	kg
Mercury compounds	4.2E-08	lb	4.2E-08	kg
Methanol	3.7E-05	lb	3.7E-05	kg
4-Methyl-2-pentanone	2.3E-08	lb	2.3E-08	kg
Molybdenum trioxide	2.2E-06	lb	2.2E-06	kg
m-Xylene	2.1E-08	lb	2.1E-08	kg

Table 44. LCI Data for the Refining of Petroleum Products
(continued)

Environmental Emissions	1,000 lb		1,000 kg	
Waterborne emissions				
Naphthalene	1.0E-06	lb	1.0E-06	kg
Nickel	4.6E-08	lb	4.6E-08	kg
Nickel compounds	5.5E-06	lb	5.5E-06	kg
Nitrate compounds	1.2E-02	lb	1.2E-02	kg
o-Xylene	2.1E-07	lb	2.1E-07	kg
PAH, polycyclic aromatic hydrocarbons	6.5E-07	lb	6.5E-07	kg
p-Xylene	2.0E-08	lb	2.0E-08	kg
Phenanthrene	9.2E-08	lb	9.2E-08	kg
Phenol	5.5E-06	lb	5.5E-06	kg
Propene	3.7E-07	lb	3.7E-07	kg
Selenium	6.4E-07	lb	6.4E-07	kg
Selenium compounds	1.8E-06	lb	1.8E-06	kg
Silver compounds	5.4E-12	lb	5.4E-12	kg
Styrene	3.9E-07	lb	3.9E-07	kg
t-Butyl methyl ether	5.4E-10	lb	5.4E-10	kg
t-Butyl alcohol	6.5E-09	lb	6.5E-09	kg
Toluene	2.5E-06	lb	2.5E-06	kg
Vanadium compounds	1.7E-05	lb	1.7E-05	kg
Xylene	5.1E-06	lb	5.1E-06	kg
Zinc compounds	2.7E-05	lb	2.7E-05	kg
Naphthalene, 2-methyl-	2.2E-08	lb	2.2E-08	kg
Acenaphthene	7.6E-10	lb	7.6E-10	kg
Acenaphthylene	7.6E-10	lb	7.6E-10	kg
Benzo(a)anthracene	3.1E-08	lb	3.1E-08	kg
Benzo(a)pyrene	3.1E-08	lb	3.1E-08	kg
Benzo(k)fluoranthene	7.6E-10	lb	7.6E-10	kg
BOD5, Biological Oxygen Demand	1.1E-02	lb	1.1E-02	kg
Chromium VI	7.6E-07	lb	7.6E-07	kg
Chromium III	2.8E-07	lb	2.8E-07	kg
Chrysene	1.8E-08	lb	1.8E-08	kg
COD, Chemical Oxygen Demand	2.7E-02	lb	2.7E-02	kg
Dibenz(a,h)anthracene	1.8E-08	lb	1.8E-08	kg
Fluorene	7.6E-10	lb	7.6E-10	kg
PAH, polycyclic aromatic hydrocarbons	9.3E-16	lb	9.3E-16	kg
Nitrogen, total	4.3E-04	lb	4.3E-04	kg
Oils, unspecified	1.5E-03	lb	1.5E-03	kg
Pyrene	1.8E-08	lb	1.8E-08	kg
Silver	6.5E-10	lb	6.5E-10	kg

Table 44. LCI Data for the Refining of Petroleum Products
(continued)

	1,000 lb		1,000 kg	
Environmental Emissions				
Waterborne Emissions				
Dissolved solids	1.9E-01	lb	1.9E-01	kg
Suspended solids, unspecified	1.7E-02	lb	1.7E-02	kg
Sulfur	1.9E-08	lb	1.9E-08	kg
TOC, Total Organic Carbon	7.1E-03	lb	7.1E-03	kg
Soil Emissions				
Benzene, 1,2,4-trimethyl-	2.6E-06	lb	2.6E-06	kg
Aluminium oxide, fibrous forms	2.4E-04	lb	2.4E-04	kg
Ammonia	1.4E-06	lb	1.4E-06	kg
Anthracene	1.3E-08	lb	1.3E-08	kg
Barium compounds	3.6E-11	lb	3.6E-11	kg
Benzene	1.4E-06	lb	1.4E-06	kg
Benzene, ethyl-	7.9E-07	lb	7.9E-07	kg
Benzo(g,h,i)perylene	3.0E-07	lb	3.0E-07	kg
Biphenyl	1.1E-08	lb	1.1E-08	kg
Butadiene	3.3E-09	lb	3.3E-09	kg
Cadmium compounds	4.9E-09	lb	4.9E-09	kg
Chromium	5.4E-10	lb	5.4E-10	kg
Chromium compounds	5.2E-07	lb	5.2E-07	kg
Cobalt compounds	6.1E-07	lb	6.1E-07	kg
Copper compounds	8.3E-07	lb	8.3E-07	kg
4-Methyl-2-methoxyphenol	1.8E-07	lb	1.8E-07	kg
Cresol	8.0E-08	lb	8.0E-08	kg
Cumene	2.1E-07	lb	2.1E-07	kg
Cyanide compounds	5.3E-08	lb	5.3E-08	kg
Cyclohexane	1.5E-07	lb	1.5E-07	kg
Dibenzofuran	3.4E-10	lb	3.4E-10	kg
Ethane, 1,2-dibromo-	1.3E-11	lb	1.3E-11	kg
Ethene	2.6E-08	lb	2.6E-08	kg
Ethene, tetrachloro-	6.9E-10	lb	6.9E-10	kg
Hexane	1.9E-06	lb	1.9E-06	kg
Hydrogen fluoride	7.1E-10	lb	7.1E-10	kg
Hydrogen sulfide	2.2E-07	lb	2.2E-07	kg
Isoprene	1.1E-09	lb	1.1E-09	kg
Lead	3.0E-09	lb	3.0E-09	kg
Lead compounds	2.7E-06	lb	2.7E-06	kg
Manganese	2.0E-08	lb	2.0E-08	kg
Manganese compounds	4.8E-07	lb	4.8E-07	kg

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Table 44. LCI Data for the Refining of Petroleum Products (continued)

	1,000 lb		1,000 kg	
Environmental Emissions				
Soil Emissions				
Mercury	8.5E-09	lb	8.5E-09	kg
Mercury compounds	8.0E-08	lb	8.0E-08	kg
Molybdenum trioxide	5.6E-06	lb	5.6E-06	kg
m-Xylene	7.8E-07	lb	7.8E-07	kg
Naphthalene	9.7E-07	lb	9.7E-07	kg
Nickel	1.6E-07	lb	1.6E-07	kg
Nickel compounds	1.7E-05	lb	1.7E-05	kg
Nitrate compounds	5.4E-05	lb	5.4E-05	kg
o-Xylene	5.4E-08	lb	5.4E-08	kg
PAH, polycyclic aromatic hydrocarbons	2.5E-06	lb	2.5E-06	kg
p-Xylene	2.1E-08	lb	2.1E-08	kg
Phenanthrene	3.8E-07	lb	3.8E-07	kg
Phenol	3.6E-08	lb	3.6E-08	kg
Propene	6.4E-08	lb	6.4E-08	kg
Selenium compounds	6.4E-11	lb	6.4E-11	kg
Styrene	8.3E-08	lb	8.3E-08	kg
Toluene	1.7E-06	lb	1.7E-06	kg
Vanadium compounds	1.6E-05	lb	1.6E-05	kg
Xylene	1.5E-05	lb	1.5E-05	kg
Zinc compounds	5.5E-06	lb	5.5E-06	kg
Solid Wastes				
Solid waste, process to landfill	5.17	lb	5.17	kg
Water Consumption	201	gal	1.68	m^3

Sources: Young, et. al. 2019, NETL, 2017b and Oak Ridge, 1996.

NATURAL GAS PRODUCTION

Natural gas is extracted from deep underground wells and is frequently co-produced with crude oil. Because of its gaseous nature, natural gas flows quite freely from wells which produce primarily natural gas, but some energy is required to pump natural gas and crude oil mixtures to the surface. The principal composition of all natural gas is methane (CH4), other components of natural gas include ethane, propane, butane, and other heavier hydrocarbons, as well as water vapor, carbon dioxide, nitrogen, and hydrogen sulfides.

Atmospheric emissions from natural gas production result primarily from unflared venting. Methane and non-combustion carbon dioxide emissions from natural gas extraction are generally process-related, with the largest source of these emissions from normal operations, system upsets, and routine maintenance. Waterborne wastes result from brines that occur when natural gas is produced in combination with oil and from produced water production from hydraulic fracturing.

There are two types of natural gas extraction processes, conventional resource extraction and unconventional resource extraction. Conventional resources are concentrations of natural gas that occur in discrete accumulations or pools. Rock formations hosting these pools traditionally have high porosity and permeability and are found below impermeable rock formations. These impervious layers form barriers to hydrocarbon migration resulting in oil and gas being trapped below them. Conventional natural gas pools are developed using vertical well bores and using minimal stimulation. Unconventional resources are natural gas-bearing units where the permeability and porosity are so low that the resource cannot be extracted economically through a vertical well bore and instead requires a horizontal well bore followed by multistage hydraulic fracturing to achieve economic production.

The term of conventional extraction applies to oil and gas which can be extracted, after the drilling operations, just by the natural pressure of the wells and pumping or compression operations. After the depletion of maturing fields, the natural pressure of the wells may be too low to produce significant quantities of oil and gas. Different techniques may be used to boost production, mainly water and gas injection or depletion compression, which are still considered conventional extraction.

Hydraulic fracturing is a technique used in "unconventional" gas production. "Unconventional" reservoirs can cost-effectively produce gas only by using a special stimulation technique, like hydraulic fracturing, or other special recovery process and technology. This is often because the gas is highly dispersed in the rock, rather than occurring in a concentrated underground location (US EPA, 2018).

Extracting unconventional gas is relatively new. Coalbed methane production began in the 1980s; shale gas extraction is even more recent. The main enabling technologies, hydraulic fracturing and horizontal drilling, have opened up new areas for oil and gas development, with particular focus on natural gas reservoirs such as shale, coalbed and tight sands.

Natural gas may also be identified as dry or wet. Wet natural gas is rich in liquid hydrocarbons, such as oil and natural gas liquid (NGL). Dry natural gas is natural gas that remains after the liquefiable hydrocarbon portion has been removed from the gas stream (i.e., gas after lease, field, and/or plant separation), and any volumes of non-hydrocarbon gases have been removed where they occur in sufficient quantity to render the gas unmarketable (US DOE, 2015).

This unit process encompasses the material outputs for the extraction of natural gas from both conventional and unconventional sources. The inputs to this unit process are natural gas, ground water, and surface water. These three inputs are natural resources and thus

enter the boundary of this unit process with no upstream environmental burdens. If the natural gas extraction site is near a source of electricity, it is financially preferable to use electrically powered equipment instead of gas-powered equipment. This is the case for extraction sites for Barnett and Marcellus Shale. The output is dehydrated natural gas that is suitable for pipeline transport and subsequent processing steps such as sweetening or, in the case of imported natural gas, liquefaction.

In 2016, an estimated 40 percent of natural gas came from conventional onshore and offshore sources including associated onshore natural gas production and an estimated 60 percent of natural gas was sourced from unconventional natural gas resources including shale well and CBM extraction (US EIA, 2017b). Natural gas extraction is characterized by six types of extraction, namely onshore conventional, offshore conventional, associated natural gas, Barnett Shale, Marcellus Shale, and coalbed methane natural gas. The natural gas extraction data set is a mix of the extraction types shown as percentages in Table 45. The input and output data for each of the subprocesses is taken from NETL unit process library with the most recent data from 2010. A brief explanation of each extraction method is provided and detailed LCI data provided in the tables that follow.

Table 45. Percentage Contribution by Type of Natural Gas Extraction

Onshore Conventional	Offshore Conventional	Associated	Barnett Shale	Marcellus Shale	Coalbed Methane
26.90%	11.30%	13.20%	27.40%	17.10%	4.20%

Conventional onshore natural gas extraction is developed using data from NETL (2010a). Conventional onshore natural gas is recovered by vertical drilling techniques. Once a conventional onshore gas well has been discovered, the natural gas reservoir does not require significant preparation or stimulation for natural gas recovery. Approximately 63 percent of U.S. natural gas production is from conventional onshore gas wells (US EIA, 2009). The conventional onshore gas wells of this analysis are assumed to have a daily production rate between 400 and 1,550 thousand cubic feet, which is characteristic of approximately 40 percent of gas wells in the U.S. (US EIA, 2009b). The key sub-systems for natural gas extraction include compression, dehydration, flaring, water use, and water quality. Table 46 provides the energy and environmental data for the extraction of 1,000 pounds and 1,000 kilograms of natural gas by the conventional onshore method.

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Table 46. LCI Data for Natural Gas Extraction (Conventional Onshore)

	1,000 lb	1,000 kg
Energy		
Process Energy		
Natural gas	913 ft^3	57.0 m^3
Environmental Emissions		
Atmospheric Emissions		
Carbon dioxide	112 lb	112 kg
Methane	1.53 lb	1.53 kg
Nitrous oxide	1.7E-04 lb	1.7E-04 kg
Nitrogen oxides	3.62 lb	3.62 kg
Sulfur dioxide	5.2E-04 lb	5.2E-04 kg
Carbon monoxide	0.28 lb	0.28 kg
NMVOC, non-methane volatile organic compounds, (	0.11 lb	0.11 kg
Particulates, > 2.5 um, and < 10um	0.0089 lb	0.0089 kg
Waterborne Releases		
Dissolved solids	3.91 lb	3.91 kg
Boron	0.0019 lb	0.0019 kg
Chloride	0.38 lb	0.38 kg
Sulfate	1.51 lb	1.51 kg
Hydrocarbons, unspecified	0.027 lb	0.027 kg
Solid Wastes		
Solid waste, process to landfill	24.7 lb	24.7 kg
Water Consumption		
Water, surface water consumption	38.2 gal	319 l
Water, groundwater consumption	38.2 gal	319 l

Sources: US EIA 2017e, US EIA 2014, NETL 2010a, US EIA 2009a, US EIA 2009b

Conventional offshore natural gas extraction is developed using data from NETL (2010b). Conventional offshore natural gas is recovered by vertical drilling techniques. Once a conventional offshore gas well has been discovered, the natural gas reservoir does not require significant preparation or stimulation for natural gas recovery. A natural gas reservoir must be large in order to justify the capital outlay for the completion of the well and construction of an offshore drilling platform. The majority of U.S. offshore wells are in the Gulf of Mexico. This analysis assumes that an offshore well produces 25 million cubic feet of natural gas per day (Offshore-technology.com, 2010). Table 47 provides the energy and environmental data for the extraction of 1,000 pounds and 1,000 kilograms of natural gas by the conventional offshore method.

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Table 47. LCI Data for Natural Gas Extraction (Conventional Offshore)

	1,000 lb	1,000 kg
Energy		
Process Energy		
Natural gas	844 ft^3	52.7 m^3
Gasoline	0.0041 gal	3.4E-05 m^3
Environmental Emissions		
Atmospheric Emissions		
Carbon dioxide	105 lb	105 kg
Methane	0.43 lb	0.43 kg
Nitrous oxide	0.0026 lb	0.0026 kg
Nitrogen oxides	0.11 lb	0.11 kg
Sulfur dioxide	0.0028 lb	0.0028 kg
Carbon monoxide	0.025 lb	0.025 kg
NMVOC, non-methane volatile organic compounds,	0.0017 lb	0.0017 kg
Particulates, > 2.5 um, and < 10um	0.0054 lb	0.0054 kg
Waterborne Releases		
BOD5, Biological Oxygen Demand	0.99 lb	0.99 kg
TOC, Total Organic Carbon	0.61 lb	0.61 kg
Nitrogen, total	0.044 lb	0.044 kg
Phosphorus, total	5.9E-04 lb	5.9E-04 kg
Dissolved solids	46.7 lb	46.7 kg
Solid Wastes		
Solid waste, process to landfill	24.7 lb	24.7 kg

Sources: US EIA 2017e, US EIA 2014, NETL 2010b, US EIA 2009a, and Offshore-technology.com 2010.

Conventional onshore associated natural gas extraction is developed using data from NETL (2010c). Associated natural gas is co-extracted with crude oil. The extraction of onshore associated gas is similar to the extraction methods for conventional onshore gas. The use of oil/gas separators is necessary to recover natural gas from the mixed product stream. The majority of these wells are assumed to be in Texas and Louisiana (US EIA, 2009c). The production rates of onshore associated gas wells are highly variable, but an average associated gas well in the U.S. produces 59 barrels of oil and 61 thousand cubic feet of natural gas per day (US EIA, 2009b). Table 48 provides the energy and environmental data for the extraction of 1,000 pounds and 1,000 kilograms of associated natural gas by the conventional onshore method.

Table 48. LCI Data for Associated Natural Gas Extraction (Conventional Onshore)

	1,000 lb	1,000 kg
Energy		
Process Energy		
Natural gas	913 ft^3	57.0 m^3
Environmental Emissions		
Atmospheric Emissions		
Carbon dioxide	112 lb	112 kg
Methane	2.53 lb	2.53 kg
Nitrous oxide	1.7E-04 lb	1.7E-04 kg
Nitrogen oxides	3.62 lb	3.62 kg
Sulfur dioxide	5.2E-04 lb	5.2E-04 kg
Carbon monoxide	0.28 lb	0.28 kg
NMVOC, non-methane volatile organic compounds,	0.21 lb	0.21 kg
Particulates, > 2.5 um, and < 10um	0.0089 lb	0.0089 kg
Waterborne Releases		
Dissolved solids	3.91 lb	3.91 kg
Boron	0.0019 lb	0.0019 kg
Chloride	0.38 lb	0.38 kg
Sulfate	1.51 lb	1.51 kg
Hydrocarbons, unspecified	0.027 lb	0.027 kg
Solid Wastes		
Solid waste, process to landfill	24.7 lb	24.7 kg
Water Consumption		
Water, surface water consumption	38.2 gal	319 l
Water, groundwater consumption	38.2 gal	319 l

Sources: US EIA 2017e, US EIA 2014, NETL 2010c, US EIA 2009a, US EIA 2009b, and US EIA 2009c.

The **Barnett shale gas extraction** is developed using data from NETL (2010d), while the **Marcellus shale gas extraction** is developed using the water use data from NETL (2010e) and the rest of the inputs and outputs from that of the Barnett shale extraction (NETL, 2010d). Natural gas is dispersed throughout the Barnett Shale formation in northern Texas and the Marcellus Shale in the northern Appalachian Basin. Shale gas cannot be recovered using conventional extraction technologies but is recovered through the use of horizontal drilling and hydraulic fracturing (hydrofracking). Horizontal drilling creates a wellbore that runs the length of a shale formation, and hydrofracking uses high pressure fluid (a mixture of water, surfactants, and proppants) for breaking apart the shale reservoir and facilitating

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the flow of natural gas. Approximately 11 percent of new pipeline capacity in 2008 (4.8 billion cubic feet per day) was installed for natural gas from Barnett Shale (US EIA, 2009c). In 2012, the overall Appalachian natural gas production was 7.8 billion cubic feet per day and has increased to 23.8 billion cubic feet per day in 2017 (US EIA, 2017f). The Marcellus shale unit process is based on the Barnet shale gas extraction unit process with water inputs from the surface and ground sources specific to the Marcellus region. Table 49 provides the energy and environmental data for the extraction of 1,000 pounds and 1,000 kilograms of Barnett shale natural gas. Table 50 provides the energy and environmental data for the extraction of 1,000 pounds and 1,000 kilograms of Marcellus shale natural gas.

The **Coal Bed Methane (CBM) natural gas extraction** is developed using data from NETL (2010f). Natural gas can be recovered from coal seams using horizontal drilling. Coalbed methane (CBM) was first extracted from coal mines as a safety measure to reduce the explosion hazard posed by methane gas in the mines. Deeper coal formations might require hydraulic fracturing to release the natural gas. The development of a well for coal bed methane requires horizontal drilling followed by a depressurization period during which naturally occurring water is discharged from the coal seam. There are viable coal bed methane deposits nationwide, but the majority of CBM production occurs in the Rocky Mountain region (ALL Consulting, 2004). Table 51 provides the energy and environmental data for the extraction of 1,000 pounds and 1,000 kilograms of natural gas from coal bed methane.

Table 49. LCI Data for Barnett Shale Natural Gas Extraction

	1,000 lb		1,000 kg	
Energy				
Process Energy				
Electricity from grid	21.0	kWh	46.2	kWh
Natural gas	698	ft^3	43.6	m^3
Environmental Emissions				
Atmospheric Emissions				
Carbon dioxide	86.3	lb	86.3	kg
Methane	1.27	lb	1.27	kg
Nitrous oxide	1.1E-04	lb	1.1E-04	kg
Nitrogen oxides	2.86	lb	2.86	kg
Sulfur dioxide	4.1E-04	lb	4.1E-04	kg
Carbon monoxide	0.22	lb	0.22	kg
NMVOC, non-methane volatile organic compounds, (	0.083	lb	0.083	kg
Particulates, > 2.5 um, and < 10um	0.0070	lb	0.0070	kg
Waterborne Releases				
Dissolved solids	3.72	lb	3.72	kg
Calcium	0.20	lb	0.20	kg
Iron	0.0011	lb	0.0011	kg
Chloride	2.05	lb	2.05	kg
Sulfate	0.0080	lb	0.0080	kg
Magnesium	0.025	lb	0.025	kg
Silicate	7.4E-04	lb	7.4E-04	kg
Solid Wastes				
Solid waste, process to landfill	24.7	lb	24.7	kg
Water Consumption				
Water, surface water consumption	66.0	gal	551	l
Water, groundwater consumption	99.0	gal	826	l

Sources: US EPA 2018, US EIA 2017e, US EIA 2014, NETL 2010d, US EIA 2009a, Hayden 2005, and US EIA 2017f.

Table 50. LCI Data for Marcellus Shale Natural Gas Extraction

	1,000 lb	1,000 kg
Energy		
Process Energy		
Electricity from grid	21.0 kWh	46.2 kWh
Natural gas	698 ft^3	43.6 m^3
Environmental Emissions		
Atmospheric Emissions		
Carbon dioxide	86.3 lb	86.3 kg
Methane	1.27 lb	1.27 kg
Nitrous oxide	1.1E-04 lb	1.1E-04 kg
Nitrogen oxides	2.86 lb	2.86 kg
Sulfur dioxide	4.1E-04 lb	4.1E-04 kg
Carbon monoxide	0.22 lb	0.22 kg
NMVOC, non-methane volatile organic compounds, u	0.083 lb	0.083 kg
Particulates, > 2.5 um, and < 10um	0.0070 lb	0.0070 kg
Waterborne Releases		
Dissolved solids	3.72 lb	3.72 kg
Calcium	0.20 lb	0.20 kg
Iron	0.0011 lb	0.0011 kg
Chloride	2.05 lb	2.05 kg
Sulfate	0.0080 lb	0.0080 kg
Magnesium	0.025 lb	0.025 kg
Silicate	7.4E-04 lb	7.4E-04 kg
Solid Wastes		
Solid waste, process to landfill	24.7 lb	24.7 kg
Water Consumption		
Water, surface water consumption	80.9 gal	675 l
Water, groundwater consumption	1.27 gal	10.6 l

Sources: US EPA 2018, US EIA 2017e, US EIA 2014, NETL 2010d, NETL 2010e, US EIA 2009d, Hayden 2005, and US EIA 2017f.

Table 51. LCI Data for Natural Gas Extraction from Coal Bed Methane

	1,000 lb	1,000 kg
Energy		
Process Energy		
Natural gas	907 ft^3	56.6 m^3
Environmental Emissions		
Atmospheric Emissions		
Carbon dioxide	112 lb	112 kg
Methane	1.56 lb	1.56 kg
Nitrous oxide	1.1E-04 lb	1.1E-04 kg
Nitrogen oxides	3.81 lb	3.81 kg
Sulfur dioxide	5.5E-04 lb	5.5E-04 kg
Carbon monoxide	0.30 lb	0.30 kg
NMVOC, non-methane volatile organic compounds,	0.11 lb	0.11 kg
Particulates, > 2.5 um, and < 10um	0.0093 lb	0.0093 kg
Waterborne Releases		
Dissolved solids	50.8 lb	50.8 kg
Calcium	0.62 lb	0.62 kg
Chloride	12.4 lb	12.4 kg
Sulfate	0.050 lb	0.050 kg
Magnesium	0.20 lb	0.20 kg
Barium	3.56 lb	3.56 kg
Bicarbonate, ion	25.2 lb	25.2 kg
Manganese	0.18 lb	0.18 kg
Sodium	11.9 lb	11.9 kg
Solid Wastes		
Solid waste, process to landfill	24.7 lb	24.7 kg

Sources: US EPA 2018, US EIA 2017e, US EIA 2014, NETL 2010f, US EIA 2009a, and ALL Consulting 2004.

NATURAL GAS PROCESSING

Once raw natural gas is extracted, it is processed to yield a marketable product. First, the heavier hydrocarbons such as ethane, butane and propane are removed and marketed as liquefied petroleum gas (LPG) or feedstocks to chemical processes. Then the water vapor, carbon dioxide, and nitrogen are removed to increase the quality and heating value of the natural gas. If the natural gas has a high hydrogen sulfide content, it is considered "sour." Before it is used, hydrogen sulfide is removed by adsorption in an amine solution—a process known as "sweetening" (US EIA, 2018).

Natural gas transported on the mainline natural gas transportation system in the United States must meet specific quality measures so that the pipeline network (or grid) can provide uniform quality natural gas. Wellhead natural gas may contain contaminants and hydrocarbon gas liquids (HGL) that must be removed before the natural gas can be safely delivered to the high-pressure, long-distance pipelines that transport natural gas to consumers (US EIA, 2018).

A natural gas processing plant typically receives natural gas from a gathering system of pipelines from natural gas and oil wells. Natural gas processing can be complex and usually involves several processes, or stages, to remove oil, water, HGL, and other impurities such as sulfur, helium, nitrogen, hydrogen sulfide, and carbon dioxide. The composition of the wellhead natural gas determines the number of stages and the processes required to produce pipeline-quality dry natural gas. These stages and processes may be integrated into one unit or operation, be performed in a different order or at alternative locations (lease/plant), or not be required at all (US EIA, 2018).

In the gas processing plant, there are basic stages that the natural gas may go through during processing/treatment. A description of each of these stages are listed here.

- Gas-oil-water separators: Pressure relief in a single-stage separator causes a natural separation of the liquids from the gases in the natural gas. In some cases, a multi-stage separation process is required to separate the different fluid streams.
- Condensate separator: Condensates are most often removed from the natural gas stream at the wellhead with separators much like gas-oil-water separators. The gas flow into the separator comes directly from the wellhead. Extracted condensate is sent to storage tanks.
- Dehydration: A dehydration process removes water that may cause the formation of undesirable hydrates and water condensation in pipelines.
- Contaminant removal: Nonhydrocarbon gases—such as hydrogen sulfide, carbon dioxide, water vapor, helium, nitrogen, and oxygen—must also be removed from the natural gas stream. The most common removal technique is to direct the natural gas though a vessel containing an amine solution. Amines absorb hydrogen sulfide and carbon dioxide from natural gas and can be recycled and regenerated for repeated use. For natural gas that is sweetened, the majority of the H2S removed is used for production of sulfur (USGS, 2008). SO2 is emitted from crude oil and natural gas production and processing operations that handle and treat sulfur-rich, or "sour," gas. Sulfur dioxide emissions are reported for flaring of H_2S that is not used for recovered sulfur production (Lattanzio, 2018).
- Nitrogen extraction: Once the hydrogen sulfide and carbon dioxide are reduced to acceptable levels, the natural gas stream is routed to a Nitrogen Rejection Unit (NRU), where it is further dehydrated using molecular sieve beds.
- Methane separation: The process of demethanizing the natural gas stream can occur as a separate operation in a natural gas processing plant or as part of the NRU operation. Cryogenic processing and absorption methods are some of the ways used to separate methane from HGL.

- Fractionation: Fractionation separates the HGL into component liquids using the varying boiling points of the individual HGL. HGL from the processing plant may be sent to petrochemical plants, oil refineries, and other HGL consumers (US EIA, 2018).

Once the natural gas has been processed, pipelines move natural gas from the processing plant to markets. Natural gas transmission pipelines are wide-diameter pipelines and are often the long-distance portion of natural gas pipeline systems that connect gathering systems in producing areas, natural gas processing plants, other receipt points, and the main consumer service areas. The three types of transmission pipelines are interstate natural gas pipelines (across state borders), intrastate natural gas pipelines (within a state), and Hinshaw natural gas pipelines (receive from interstate and deliver to consumers). When natural gas arrives at the communities where it will be used (usually through large pipelines), it flows into smaller diameter pipelines called mains and then into smaller service lines that go directly to homes or buildings (US EIA, 2018).

Two natural gas processing unit processes were used in this analysis, one for conventional natural gas and one for shale-derived natural gas. The inputs and emissions data for both these processes are based on the GREET 2017 model (ANL, 2017). For both conventional and shale-derived natural gas processing unit processes, the inputs include energy and water, and outputs include emissions to air. Extracted natural gas is transported primarily by pipeline. Pipeline transportation data were calculated from the total marketed production of natural gas in the U.S. in 2017 (EIA, 2017g) and the annual mileage of natural gas transmission and gathering pipeline in the U.S. (PHMSA, 2018).

Table 52 shows the energy and emissions data for processing 1,000 pounds and 1,000 kilograms of conventional natural gas. Table 53 provides the LCI data from processing 1,000 pounds and 1,000 kilograms of shale-derived natural gas.

Table 52. LCI Data for Conventional Natural Gas Processing

	1,000 lb	1,000 kg
Material Inputs		
Natural gas	1000 lb	1000 kg
Energy		
Process Energy		
Electricity from grid	4.85 kWh	10.7 kWh
Natural gas	10.9 ft^3	0.68 m^3
Diesel	0.040 gal	3.3E-04 m^3
Transportation Energy		
Pipeline	0.12 ton·mi	0.38 tonne·km
Environmental Emissions		
Atmospheric Emissions		
VOC, volatile organic compounds	0.20 lb	0.20 kg
Carbon monoxide	0.093 lb	0.093 kg
Nitrogen oxides	0.12 lb	0.12 kg
Particulates, < 10 um	0.0054 lb	0.0054 kg
Particulates, < 2.5 um	0.0049 lb	0.0049 kg
Sulfur oxides	0.45 lb	0.45 kg
Methane	0.27 lb	0.27 kg
Nitrogen dioxide	5.1E-04 lb	5.1E-04 kg
Carbon dioxide, fossil	0.095 lb	0.095 kg
Water Consumption	34.5 gal	288 l

Sources: ANL 2017, US EIA 2018, USGS 2008, Lattanzio 2018, US EIA 2017g, PHMSA 2018.

Table 53. LCI Data for Shale-Derived Natural Gas Processing

	1,000 lb	1,000 kg
Material Inputs		
Natural gas	1000 lb	1000 kg
Energy		
Process Energy		
Electricity from grid	4.85 kWh	10.7 kWh
Natural gas	10.9 ft^3	0.68 m^3
Diesel	0.040 gal	3.3E-04 m^3
Transportation Energy		
Pipeline	0.12 ton·mi	0.38 tonne·km
Environmental Emissions		
Atmospheric Emissions		
VOC, volatile organic compounds	0.20 lb	0.20 kg
Carbon monoxide	0.097 lb	0.097 kg
Nitrogen oxides	0.13 lb	0.13 kg
Particulates, < 10 um	0.0059 lb	0.0059 kg
Particulates, < 2.5 um	0.0054 lb	0.0054 kg
Sulfur oxides	0.45 lb	0.45 kg
Methane	0.27 lb	0.27 kg
Nitrogen dioxide	6.5E-04 lb	6.5E-04 kg
Carbon dioxide, fossil	1.0E-04 lb	1.0E-04 kg
Water Consumption	34.5 gal	288 l

Sources: ANL 2017, US EIA 2018, USGS 2008, Lattanzio 2018, US EIA 2017g, PHMSA 2018.

OLEFINS PRODUCTION

The primary process used in this analysis for manufacturing olefins is the thermal cracking, or steam cracking, of saturated hydrocarbons such as ethane, propane, naphtha, and other gas oils. Although steam cracking data has been provided for this analysis, many of the olefins here can be manufactured by a number of technologies. Due to the abundance of propane, ethane, and methane from shale gas, lighter alternative feedstocks are now used more frequently[26]. Coal, biomass and other feedstocks are used in used in smaller proportions to create olefins, but steam cracking will likely remain a leading technology for the manufacture of olefins[27]. Propylene mainly comes from steam cracking or as a by-

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[26] Amghizar, Ismaël, et.al. Engineering. New Trends in Olefin Production, March 16, 2017. Vol. 3. pp 171–178.
[27] Ibid.

product of refining, although some propylene is created through propane dehydrogenation (PDH), olefin metathesis, methanol synthesis, and coal to olefins. Butadiene mainly comes from steam cracking with small amounts produced from ethanol[28]. Pyrolysis gas is commonly manufactured in steam crackers, then may be further processed to create a BTX stream used to produce benzene, toluene, and xylenes.

Typical production of ethylene, propylene, and other coproducts begins when hydrocarbons are fed to the cracking furnace. After being pre-heated by a heat exchanger, mixed with steam and then further heated, the hydrocarbon feed is transferred to a reactor.   The temperature is again increased to around 800 Celsius, and the cracked gas products are immediately cooled in quench towers using quench oil or quench water. Fuel oil is separated from the main gas stream in a multi-stage centrifugal compressor. The main gas stream then undergoes acid gas removal and drying to remove any moisture that may remain from the quenching process prior to cracked gas compression. The final step involves fractional distillation of the various reaction products and is achieved using a series of distillation columns and hydrogenation reactors.

Within the hydrocracker, an offgas is produced from the raw materials entering. A portion of this offgas is processed and used as fuel gas to produce steam for the hydrocracker, while the remaining portion is exported from the hydrocracker as a coproduct. This internally-created energy is included in the analysis by including the production of the raw materials combusted to produce the energy as well as the energy amount attributed to the combustion of those raw materials. Unlike the raw materials that become part of the product output mass, no material feedstock energy is assigned to the raw materials inputs that are combusted within the process. This offgas used within the process is shown as a weight of natural gas and petroleum input to produce the energy.

An individual weighted average for three leading olefins producers (10 thermal cracking units) was calculated using the production amounts from each plant for ethylene, propylene, pyrolysis gasoline and butadiene. All companies provided data for the year 2015. A weighted average was calculated for each of the olefins from the data collected and used to develop the LCA model. Propylene, pyrolysis gasoline and butadiene are among the coproducts of ethylene production, and a mass basis was used to allocate the credit for the coproducts. Numerous coproduct streams are produced during this process. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel use. For coproducts sold for fuel use in other processes, these were treated as an avoided fuel product and were given credits based on the fuel they would replace.

The captured ethylene production amount is approximately 10 percent of the ethylene production in the U.S. in 2015 (OGJ, 2017). The captured propylene production amount is estimated to be 4 percent of the total propylene production in the U.S. in 2015 (OGJ, 2017). While data was collected from a relatively small sample of plants, the olefins producers who provided data for this module verified that the characteristics of their plants are

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[28] Dussol,D. et.al. Chemical Engineering Journal. New Insights of Butadiene Production from Ethanol: Elucidation of Concurrent Reaction Pathways and Kinetic Study. November 26, 2019. 123586.

representative of a variety of ages from older plants to state-of-the-art. Of the ten plants, two plants were using older technology, five plants were using average technology and three plants were using state-of the art technology in 2015.

Data providers reviewed their data as well as the average olefins LCI data and provided questions on comments on the average, which Franklin Associates reviewed and responded until all companies understood and accepted the average dataset.

Table 54 shows the averaged energy and emissions data for the production of 1,000 pounds and 1,000 kilograms of ethylene. Table 55 shows the averaged energy and emissions data for the production of 1,000 pounds and 1,000 kilograms of propylene. Table 56 shows the averaged energy and emissions data for the production of 1,000 pounds and 1,000 kilograms of pyrolysis gasoline. As a mass basis was used for the olefins unit process allocation, the differences in the individual olefins average data are due to differences in the amounts created at the plants participating as well as the amounts produced at the plants which are used as a weighting. Due to confidentiality issues, butadiene energy and emissions data is not publicly available.

In the case of some emissions, data was provided by fewer than the 3 producers. To indicate known emissions while protecting the confidentiality of individual company responses, some emissions are reported only by the order of magnitude of the average.

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Table 54. LCI Data for the Production of Ethylene

	1,000 lb	1,000 kg	
Material Inputs (1)			
Refined Petroleum Products	104 lb	104 kg	
(42% naphtha, 58% refinery gases)			
Processsesed Natural Gas	896 lb	896 kg	
(50% ethane, 32% propane, 6% butane, 12% ethane/propane mix)			
Internal off-gas (2)			
From oil	19.4 lb	19.4 kg	
From natural gas	154 lb	154 kg	
	1,000 lb	**1,000 kg**	
Energy			
Process Energy			
Electricity from grid	12.7 kWh	28.0 kWh	
Electricity from cogen	12.2 kWh	27.0 kWh	
Natural gas	1,860 ft^3	116 m^3	
Fuel Gas	1,805 ft^3	113 m^3	
Landfill gas	11.6 ft^3	0.72 m^3	
Avoided Energy			
Oil sold as co-product	0.37 gal	0.0031 m^3	
Recovered energy from exported steam	217 ft^3	13.6 m^3	
Off-gas sold	607 ft^3	37.9 m^3	
Transportation Energy			
Barge	25.8 ton·mi	83.0 tonne·km	
Pipeline -refinery products	0.48 ton·mi	1.56 tonne·km	
Pipeline -natural gas products	256 ton·mi	826 tonne·km	
	1,000 lb	**1,000 kg**	
Environmental Emissions			
Atmospheric Emissions			
Particulates, unspecified	0.010 lb	0.010 kg	*
Particulates, < 2.5 um	0.025 lb	0.025 kg	
Particulates, > 2.5 um, and < 10um	0.0049 lb	0.0049 kg	
Nitrogen oxides	0.29 lb	0.29 kg	
NMVOC, non-methane volatile organic compounds, ı	0.12 lb	0.12 kg	
VOC, volatile organic compounds	0.010 lb	0.010 kg	*
Sulfur oxides	0.020 lb	0.020 kg	
Carbon dioxide, fossil	640 lb	640 kg	
Methane, fossil	0.10 lb	0.10 kg	
Nitrous oxide	0.20 lb	0.20 kg	
Carbon monoxide	0.26 lb	0.26 kg	
Hydrogen sulfide	1.0E-06 lb	1.0E-06 kg	*
Ammonia	0.0010 lb	0.0010 kg	*
Chlorine	1.0E-05 lb	1.0E-05 kg	*

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Table 54. LCI Data for the Production of Ethylene
(Continued)

	1,000 lb	1,000 kg	
Environmental Emissions			
Waterborne Releases			
Benzene	0.010 lb	0.010 kg	*
BOD5, Biological Oxygen Demand	0.0039 lb	0.0039 kg	
COD, Chemical Oxygen Demand	0.40 lb	0.40 kg	
Benzene, ethyl-	0.0010 lb	0.0010 kg	*
Phenol	1.0E-04 lb	1.0E-04 kg	*
Styrene	0.010 lb	0.010 kg	*
Suspended solids, unspecified	0.010 lb	0.010 kg	*
Toluene	0.010 lb	0.010 kg	*
TOC, Total Organic Carbon	1.0E-06 lb	1.0E-06 kg	*
Xylene	0.0010 lb	0.0010 kg	*
Dissolved solids	1.0E-05 lb	1.0E-05 kg	*
Cyanide	1.0E-06 lb	1.0E-06 kg	*
Nickel	1.0E-06 lb	1.0E-06 kg	*
Mercury	1.0E-07 lb	1.0E-07 kg	*
Lead	1.0E-07 lb	1.0E-07 kg	*
Ammonia	0.0010 lb	0.0010 kg	*
Ethylene glycol	0.0010 lb	0.0010 kg	*
Propylene glycol	0.0010 lb	0.0010 kg	*
Ethene	0.010 lb	0.010 kg	*
Butadiene	0.0010 lb	0.0010 kg	*
Isoprene	1.0E-04 lb	1.0E-04 kg	*
Cresol	1.0E-05 lb	1.0E-05 kg	*
Biphenyl	0.0010 lb	0.0010 kg	*
7,12-Dimethylbenz(a)anthracene	1.0E-05 lb	1.0E-05 kg	*
3-Methylcholanthrene	1.0E-06 lb	1.0E-06 kg	*
Sodium Bisulfate	1.0E-05 lb	1.0E-05 kg	*
Dimethyl phthalate	1.0E-04 lb	1.0E-04 kg	*
Dibenz(a,j)acridine	1.0E-06 lb	1.0E-06 kg	*
Solid Wastes			
Solid waste, process to landfill	0.32 lb	0.32 kg	
Solid waste, process to incineration	6.00 lb	6.00 kg	
Solid waste, process to waste-to-energy incineration	6.1E-04 lb	6.1E-04 kg	
Solid Waste Sold for Recycling or Reuse	0.30 lb	0.30 kg	
Hazardous waste to landfill	0.0031 lb	0.0031 kg	
Hazardous waste to incineration	1.40 lb	1.40 kg	

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Table 54. LCI Data for the Production of Ethylene
(Continued)

	1,000 lb	1,000 kg
Water Consumption	419 gal	3,500 l

* To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by the order of magnitude of the average.

(1) Specific input materials from oil refining and natural gas processing include ethane, propane, liquid feed, heavy raffinate, and DNG.

(2) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source

Source: Primary Data, 2018

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Table 55. LCI Data for the Production of Propylene

	1,000 lb	1,000 kg	
Material Inputs (1)			
Refined Petroleum Products	140 lb	140 kg	
(13% naphtha, 87% refinery gases)			
Processesed Natural Gas	870 lb	870 kg	
(44% ethane, 22% propane, 10% butane, 24% ethane/propane mix)			
Internal off-gas (2)			
From oil	27.0 lb	27.0 kg	
From natural gas	160 lb	160 kg	
Energy			
Process Energy			
Electricity from grid	13.9 kWh	30.6 kWh	
Electricity from cogen	10.5 kWh	23.0 kWh	
Natural gas	1,810 ft^3	113 m^3	
Fuel Gas	1,844 ft^3	115 m^3	
Landfill gas	8.17 ft^3	0.51 m^3	
Avoided Energy			
Oil sold as co-product	0.34 gal	0.0028 m^3	
Recovered energy from exported steam	228 ft^3	14.2 m^3	
Off-gas sold	716 ft^3	44.7 m^3	
Transportation Energy			
Barge	24.6 ton·mi	79 tonne·km	
Pipeline -refinery products	0.62 ton·mi	2.00 tonne·km	
Pipeline -natural gas products	270 ton·mi	868 tonne·km	
Environmental Emissions			
Atmospheric Emissions			
Particulates, unspecified	0.010 lb	0.010 kg	*
Particulates, < 2.5 um	0.028 lb	0.028 kg	
Particulates, > 2.5 um, and < 10um	0.0056 lb	0.0056 kg	
Nitrogen oxides	0.30 lb	0.30 kg	
NMVOC, non-methane volatile organic compounds,	0.12 lb	0.12 kg	
VOC, volatile organic compounds	0.010 lb	0.010 kg	*
Sulfur oxides	0.019 lb	0.019 kg	
Carbon dioxide, fossil	642 lb	642 kg	
Methane, fossil	0.10 lb	0.10 kg	
Nitrous oxide	0.20 lb	0.20 kg	
Carbon monoxide	0.25 lb	0.25 kg	
Hydrogen sulfide	1.0E-07 lb	1.0E-07 kg	*
Ammonia	1.0E-04 lb	1.0E-04 kg	*
Chlorine	1.0E-05 lb	1.0E-05 kg	*

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Table 55. LCI Data for the Production of Propylene
(Continued)

	1,000 lb	1,000 kg	
Environmental Emissions			
Waterborne Releases			
Benzene	0.010 lb	0.010 kg	*
BOD5, Biological Oxygen Demand	0.0039 lb	0.0039 kg	
COD, Chemical Oxygen Demand	0.46 lb	0.46 kg	
Benzene, ethyl-	0.0010 lb	0.0010 kg	*
Phenol	1.0E-04 lb	1.0E-04 kg	*
Styrene	0.010 lb	0.010 kg	*
Suspended solids, unspecified	0.010 lb	0.010 kg	*
Toluene	0.010 lb	0.010 kg	*
TOC, Total Organic Carbon	1.0E-06 lb	1.0E-06 kg	*
Xylene	0.0010 lb	0.0010 kg	*
Dissolved solids	1.0E-05 lb	1.0E-05 kg	*
Cyanide	1.0E-06 lb	1.0E-06 kg	*
Nickel	1.0E-06 lb	1.0E-06 kg	*
Mercury	1.0E-07 lb	1.0E-07 kg	*
Lead	1.0E-07 lb	1.0E-07 kg	*
Ammonia	0.0010 lb	0.0010 kg	*
Ethylene glycol	0.0010 lb	0.0010 kg	*
Propylene glycol	0.0010 lb	0.0010 kg	*
Ethene	0.010 lb	0.010 kg	*
Butadiene	0.0010 lb	0.0010 kg	*
Isoprene	1.0E-04 lb	1.0E-04 kg	*
Cresol	1.0E-05 lb	1.0E-05 kg	*
Biphenyl	0.0010 lb	0.0010 kg	*
7,12-Dimethylbenz(a)anthracene	1.0E-05 lb	1.0E-05 kg	*
3-Methylcholanthrene	1.0E-06 lb	1.0E-06 kg	*
Sodium Bisulfate	1.0E-05 lb	1.0E-05 kg	*
Dimethyl phthalate	1.0E-04 lb	1.0E-04 kg	*
Dibenz(a,j)acridine	1.0E-06 lb	1.0E-06 kg	*
Solid Wastes			
Solid waste, process to landfill	0.29 lb	0.29 kg	
Solid waste, process to incineration	5.70 lb	5.70 kg	
Solid waste, process to waste-to-energy incineration	5.8E-04 lb	5.8E-04 kg	
Solid Waste Sold for Recycling or Reuse	0.21 lb	0.21 kg	
Hazardous waste to landfill	0.0035 lb	0.0035 kg	
Hazardous waste to incineration	1.33 lb	1.33 kg	

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Table 55. LCI Data for the Production of Propylene
(Continued)

	1,000 lb	**1,000 kg**
Water Consumption	399 gal	3.33 m^3

* To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by the order of magnitude of the average.
(1) Specific input materials from oil refining and natural gas processing include ethane, propane, liquid feed, heavy raffinate, and DNG.
(2) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source

Source: Primary Data, 2018

Table 56. LCI Data for the Production of Pyrolysis Gasoline

	1,000 lb	**1,000 kg**
Material Inputs (1)		
Refined Petroleum Products	110 lb	110 kg
(42% naphtha, 58% refinery gases)		
Processesed Natural Gas	890 lb	890 kg
(50% ethane, 33% propane, 6% butane, 11% ethane/propane mix)		
Internal off-gas (2)		
From oil	21.0 lb	21.0 kg
From natural gas	160 lb	160 kg
Energy		
Process Energy		
Electricity from grid	12.37 kWh	27.3 kWh
Electricity from cogen	11.4 kWh	25.1 kWh
Natural gas	1,728 ft^3	108 m^3
Fuel Gas	2,010 ft^3	125 m^3
Landfill gas	8.17 ft^3	0.51 m^3
Avoided Energy		
Oil sold as co-product	0.38 gal	0.0032 m^3
Recovered energy from exported steam	259 ft^3	16.2 m^3
Off-gas sold	589 ft^3	36.8 m^3
Transportation Energy		
Barge	28.1 ton·mi	90 tonne·km
Pipeline -refinery products	0.47 ton·mi	1.52 tonne·km
Pipeline -natural gas products	256 ton·mi	823 tonne·km

Table 56. LCI Data for the Production of Pyrolysis Gasoline
(Continued)

	1,000 lb	1,000 kg	
Environmental Emissions			
Atmospheric Emissions			
Particulates, unspecified	0.010 lb	0.010 kg	*
Particulates, < 2.5 um	0.025 lb	0.025 kg	
Particulates, > 2.5 um, and < 10um	0.0048 lb	0.0048 kg	
Nitrogen oxides	0.29 lb	0.29 kg	
NMVOC, non-methane volatile organic compounds, ᵤ	0.12 lb	0.12 kg	
VOC, volatile organic compounds	0.010 lb	0.010 kg	*
Sulfur oxides	0.021 lb	0.021 kg	
Carbon dioxide, fossil	641 lb	641 kg	
Methane, fossil	0.10 lb	0.10 kg	
Nitrous oxide	0.22 lb	0.22 kg	
Carbon monoxide	0.27 lb	0.27 kg	
Hydrogen sulfide	1.0E-06 lb	1.0E-06 kg	*
Ammonia	0.0010 lb	0.0010 kg	*
Chlorine	1.0E-05 lb	1.0E-05 kg	*
Waterborne Releases			
Benzene	0.010 lb	0.010 kg	*
BOD5, Biological Oxygen Demand	0.0035 lb	0.0035 kg	
COD, Chemical Oxygen Demand	0.39 lb	0.39 kg	
Benzene, ethyl-	0.0010 lb	0.0010 kg	*
Phenol	1.0E-04 lb	1.0E-04 kg	*
Styrene	0.010 lb	0.010 kg	*
Suspended solids, unspecified	0.010 lb	0.010 kg	*
Toluene	0.010 lb	0.010 kg	*
TOC, Total Organic Carbon	1.0E-06 lb	1.0E-06 kg	*
Xylene	0.0010 lb	0.0010 kg	*
Dissolved solids	1.0E-05 lb	1.0E-05 kg	*
Cyanide	1.0E-06 lb	1.0E-06 kg	*
Nickel	1.0E-06 lb	1.0E-06 kg	*
Mercury	1.0E-07 lb	1.0E-07 kg	*
Lead	1.0E-07 lb	1.0E-07 kg	*
Ammonia	0.0010 lb	0.0010 kg	*
Ethylene glycol	0.0010 lb	0.0010 kg	*
Propylene glycol	0.0010 lb	0.0010 kg	*
Ethene	0.010 lb	0.010 kg	*
Butadiene	0.0010 lb	0.0010 kg	*
Isoprene	1.0E-04 lb	1.0E-04 kg	*
Cresol	1.0E-05 lb	1.0E-05 kg	*
Biphenyl	0.0010 lb	0.0010 kg	*
7,12-Dimethylbenz(a)anthracene	1.0E-05 lb	1.0E-05 kg	*
3-Methylcholanthrene	1.0E-06 lb	1.0E-06 kg	*
Sodium Bisulfate	1.0E-05 lb	1.0E-05 kg	*
Dimethyl phthalate	1.0E-04 lb	1.0E-04 kg	*
Dibenz(a,j)acridine	1.0E-06 lb	1.0E-06 kg	*

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Table 56. LCI Data for the Production of Pyrolysis Gasoline
(Continued)

	1,000 lb	1,000 kg
Solid Wastes		
Solid waste, process to landfill	0.32 lb	0.32 kg
Solid waste, process to incineration	6.50 lb	6.50 kg
Solid waste, process to waste-to-energy incineration	6.6E-04 lb	6.6E-04 kg
Solid Waste Sold for Recycling or Reuse	0.21 lb	0.21 kg
Hazardous waste to landfill	0.0030 lb	0.0030 kg
Hazardous waste to incineration	1.52 lb	1.52 kg
Water Consumption	403 gal	3.36 m^3

* To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by the order of magnitude of the average.

(1) Specific input materials from oil refining and natural gas processing include ethane, propane, liquid feed, heavy raffinate, and DNG.

(2) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source

Source: Primary Data, 2018

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