CRADLE-TO-GATE LIFE CYCLE ANALYSIS OF HIGH-DENSITY POLYETHYLENE (HDPE) RESIN

Final Report

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Submitted by:

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A Division of ERG

PREFACE

This life cycle assessment of HDPE resin 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. LCI plastics database. The report was made possible through the cooperation of ACC member companies, who provided data for the production of olefins and HDPE resin.

This report was prepared for ACC by Franklin Associates, A Division of Eastern Research Group, Inc. as an independent contractor. This project was managed by Melissa Huff, Senior 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 preparation. Ben Young assisted with research.

Franklin Associates gratefully acknowledges the significant contribution to this project by Mike Levy, Keith Christman, and Prapti Muhuri of ACC in leading this project. Also acknowledged are the following companies: Chevron Phillips Chemical Corporation, ExxonMobil Corporation, INEOS Olefins and Polymers, USA, NOVA Chemical Corporation, and Dow, who graciously provided primary Life Cycle Inventory data for HDPE production. Their effort in collecting data has added considerably to the quality of this LCA report. Finally, thank you to the subset of ACC members who thoroughly reviewed this report.

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

October, 2020

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LIST OF ACRONYMS

(Alphabetical)

ACC	AMERICAN CHEMISTRY COUNCIL
AP	ACIDIFICATION POTENTIAL
API	AMERICAN PETROLEUM INSTITUTE
BOD	BIOCHEMICAL OXYGEN DEMAND
BTEX	BENZENE, TOLUENE, ETHYLBENZENE, AND XYLENE
COD	CHEMICAL OXYGEN DEMAND
CFC	CHLOROFLUOROCARBON
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
HDPE	HIGH-DENSITY POLYETHYLENE
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
MM	MILLION
NAICS	NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM

NAPAP	NATIONAL ACID PRECIPITATION ASSESSMENT PROGRAM
NGL	NATURAL GAS LIQUID
NMVOC	NON-METHANE VOLATILE ORGANIC COMPOUNDS
NREL	NATIONAL RENEWABLE ENERGY LABORATORY
ODP	OZONE DEPLETION POTENTIAL
POCP	PHOTOCHEMICAL SMOG FORMATION (HISTORICALLY PHOTOCHEMICAL OXIDANT CREATION POTENTIAL)
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
WTE	WASTE-TO-ENERGY INCINERATION

CRADLE-TO-GATE LIFE CYCLE ASSESSMENT OF HIGH-DENSITY POLYETHYLENE (HDPE)

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 High-density Polyethylene (HDPE) resin, which is used for the production of a variety of materials including bottles, household and industrial packaging, and pipes in North America. 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.

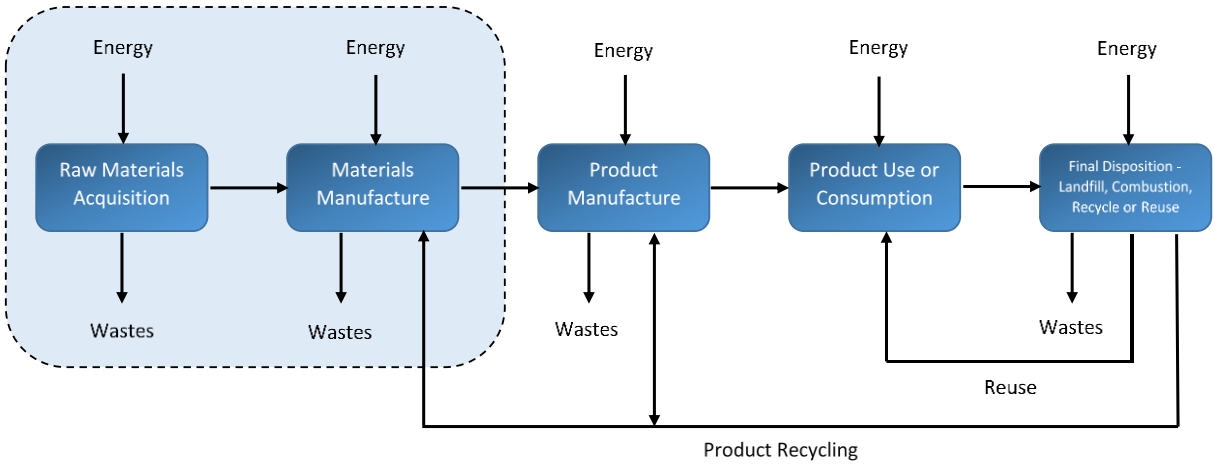

Figure 1. General materials flow for "cradle-to-grave" analysis of a product system. The dashed box indicates the boundaries of this analysis.

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.

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 HDPE resin. It is considered a cradle-to-gate boundary system because this analysis ends with the HDPE resin production. The system boundaries stop at the HDPE resin production so that the resin data can be linked to a fabrication process where it is an input material, and end-of-life data to create full life cycle inventories for a variety of products, such as bottles, various parts, and packaging. 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[1].

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 the HDPE unit process is shown separately in the attached Appendix. The LCI data for the olefins system is shown in the appendix of a separate report, ***Cradle-to-Gate Life Cycle Analysis of Olefins[2].*** All 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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1 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.

2 **Cradle-to-Gate Life Cycle Analysis of Olefins.** Franklin Associates, a Division of ERG. Submitted to the Plastics Division of the American Chemistry Council (ACC). April, 2020.

STUDY GOAL AND INTENDED USE

The purpose of this LCA is to document the LCI data and then evaluate the environmental profile of HDPE resin. 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 HDPE resin and
- to provide information about the environmental burdens associated with the production of HDPE resin. The LCA results for HDPE production can be used as a benchmark for evaluating future updated HDPE 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 HDPE resin is its forming into various products, for example, milk and juice bottles, containers for household hygiene and cleaning products, or pipes. As the study boundary concludes at the HDPE resin, 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 HDPE resin 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 HDPE resin manufacture:

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

This report presents LCI results, as well as LCIA results, for the production of HDPE resin manufacture. Figure 2 presents the flow diagram for the production of HDPE resin. A unit process description and tables for each box shown in the flow diagram can be found in the attached appendix.

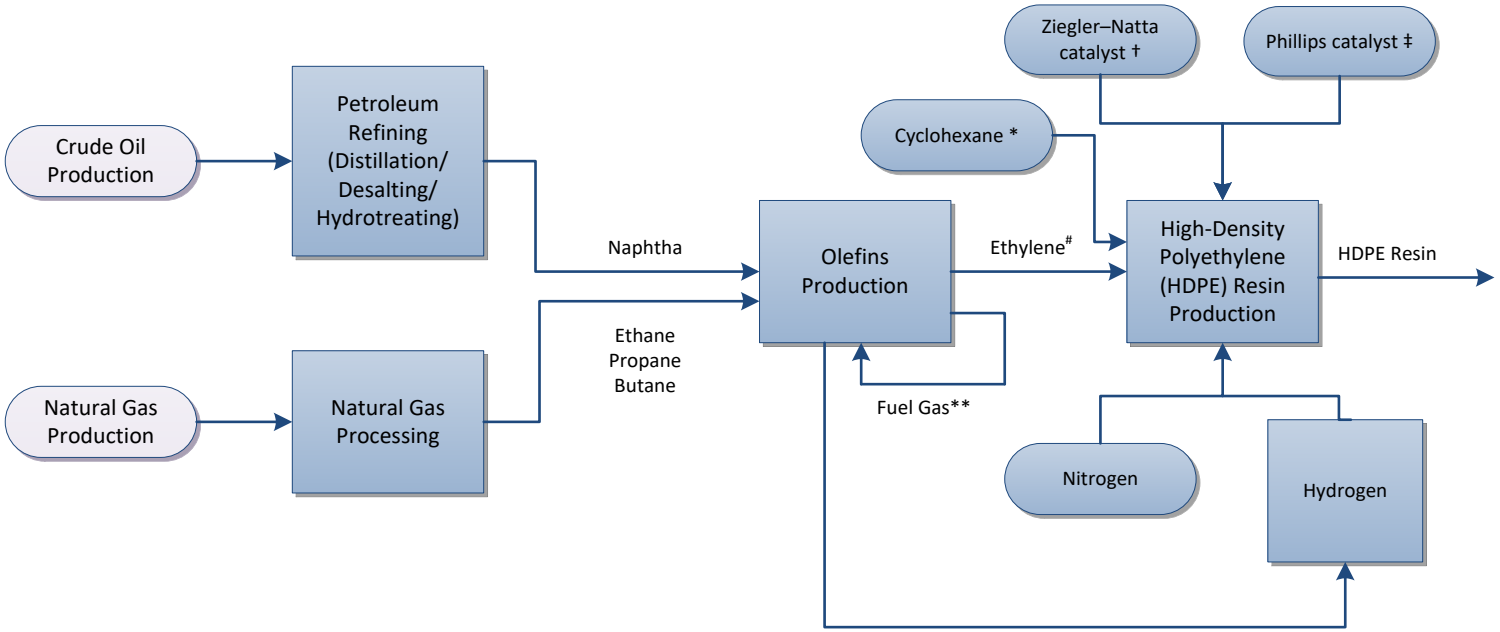

Figure 2. Flow diagram for the Production of High-Density Polyethylene (HDPE).

* Cyclohexane and nitrogen data are from ecoinvent and are adapted to U.S. conditions. Both inputs are ancillary material inputs.
**Fuel gas used for energy is created from off-gas produced in the process.
Represents ethylene production and butene, hexene-1, isobutane, and isopentane production which use ethylene as a surrogate.
† Modeled as the included titanium metal portion of catalyst only.
‡ Modeled as the included chromium metal and silica gel (SiO2) portion of catalyst only.

Technological Scope – Low Pressure Reactors

The HDPE resin is commonly polymerized in low pressure reactors. Both gas-phase and slurry loop reactors were used by data providers. A third type of low pressure technology, solution, is also used in the U.S. but is not represented in this dataset. According to older sources, solution technology is used for approximately 10 percent of the total HDPE production, with slurry technology producing the most HDPE resin (65%) and gas-phase technology producing the remaining[3]. However, newer sources show that the slurry and gas-phase technologies are closer to 40 percent each by 2015. Hybrid technologies of slurry and gas phase are also available and used. Normally a Phillips, Ziegler-Natta and/or metallocene catalysts are required during the process. The metal mining and processing for titanium (ZN catalyst) and chromium and silica gel used in the Phillips catalyst were included due to uncertainty that those materials could be more than one percent of certain LCIA categories. Each company provided estimates of the amounts of metals within their catalysts.

The gas-phase reactor is able to produce both HDPE and LLDPE in the same reactor and is the leading technology for new plants since the 1980s.[4] This is usually done in a fluidized bed reactor. Here a gas stream containing monomer recycles through the bed of polymer. Catalyst activators, comonomers, and hydrogen are fed through the bed. The reaction temperatures range from 70 to 120 C and at a pressure of 20 to 30 bar.[5] Polymer is discharged occasionally into a tank system to separate gas from solid.

The slurry loop reactor is a continuous stirred-tank reactor. In this technology, the slurry includes undissolved polymer as well as diluent, ethylene, comonomer, catalyst(s), and hydrogen. These components are continuously supplied through the loop. Some of the slurry, containing high amounts of solid, are discharged and the solids are separated while the remaining fluid is recycled back into the reactor. Chrome, Ziegler-Natta, and metallocene catalysts can be used in this technology.

Temporal and Geographic Scope

For the HDPE resin primary data, companies were requested to provide data for the year 2015, the most recent full year of HDPE resin 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. Four of the five companies provided data for the year 2015, and one company provided data for the year 2016. After reviewing individual company data in comparison to the average, each

[3] Syed, Faisal H. and William D. Vernon. Status of Low Pressure PE Process Licensing. Chemical Market Resources, Inc. Volume 7. Issue No 6. June/July 2002.
[4] Chatterjee, Ananda, and Mark A. Spalding (Eds.) (2017). Handbook of Industrial Polyethylene and Technology. Wiley.
[5] Ibid.

manufacturer verified their data from either 2015, or 2016 in one case, was representative of an average year for HDPE resin production at their company.

The geographic scope of the analysis is the manufacture of HDPE resin in North America. All HDPE resin 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. In the case of cyclohexane and nitrogen, both ancillary materials, ecoinvent data was adapted to US conditions. 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 catalyst portions, 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. Due to uncertainty of impacts from metals used in catalysts for HDPE, titanium, chromium, and silica gel were included, although the results from these materials were smaller than originally estimated.
- **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 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:

Table 1. Summary of LCI/LCIA Impact Categories

	Impact/Inventory Category	Description	Unit	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

[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.

	Impact/Inventory Category	Description	Unit	LCIA/LCI Methodology
	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 (NMVOC), CH_4, C_2H_6, C_4H_{10}, C_3H_8, C_6H_{14}, acetylene, Et-OH, formaldehyde	Lb kg O_3 eq and kg O_3 eq	TRACI v2.1

- 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. Material resource energy is provided by source.
- 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.

DATA SOURCES

The purpose of this study is to develop a life cycle profile for HDPE resin using the most recent data available for each process. A weighted average was calculated for the HDPE resin data (production for the year 2015-2016) collected for this analysis. The ethylene/hydrogen from steam cracking data was also calculated from an average of primary datasets for 2015. 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 HDPE resin were collected from five producers (ten plants) in North America – the United States and Canada. Four companies provided data for the year 2015 and one company provided data for the year 2016. A weighted average was calculated from the data collected and used to develop the LCA model. The captured HDPE resin production amount is approximately 63 percent[8] of the HDPE resin production in the U.S. in 2015. Only small amounts of isomers and off-spec/scrap PE are coproducts of HDPE resin production, and a mass basis was used to allocate the credit for the coproducts.

LCI data for the production of olefins, including ethylene and hydrogen were collected from three producers (ten plants) in North America – the United States and Canada. All companies provided data for the year 2015. A weighted average was calculated from the data collected and used to develop the LCA model. Hydrogen is a coproduct of ethylene production, and a mass basis was used to allocate the environmental burdens among these coproducts.

The data for the remaining materials (natural gas, petroleum, cyclohexane and nitrogen) used to produce HDPE resin are from secondary sources. The cyclohexane, nitrogen, and HDPE process descriptions and LCI data are provided in the Appendix at the end of this report. Other unit processes can be found in the separate report, **Cradle-to-Gate Life Cycle Analysis of Olefins**.

[8] Calculations using Plastics Industry Producers' Statistics Group (PIPS), as compiled by Vault Consulting, LLC, American Chemistry Council, U.S. Resin Production & Sales 2017 vs. 2016, March, 2018.

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 HDPE resin is 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, five companies each provided current, geographically representative data for all primary data collected for this LCA.

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[9]. 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). The cyclohexane and nitrogen inputs for HDPE resin and some small additives from petroleum refining are the only processes 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: HDPE resin manufactured in North America is regularly produced using slurry loop or gas phase low-pressure reactor or a hybrid of these. HDPE resin producers from the United States and Canada provided data from their facilities using technology ranging from old to average to state-of-the-art. This is possibly due to the technology itself being older (1960s), while some plants have considered updates to plants and catalysts/processes as state-of-the-art. The slurry-loop reactor is the older of the two types of reactor used to produce HDPE resin. Many of the plants producing HDPE resin have hybrids using both types of reactor.

Primary data were collected from HDPE manufacturers from the year 2015 and 2016. Companies providing data were given the option to collect data from the year preceding or

[9] 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].

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 or 2016 was a representative year for HDPE 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 for refined 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 HDPE resin 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 HDPE resin production amount (63 percent[10]) is more than half of the total HDPE resin production in North America, data from this analysis was used to develop the most representative average for HDPE resin production in 2015-2016 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 HDPE resin and steam cracking of the

[10] Calculations using Plastics Industry Producers' Statistics Group (PIPS), as compiled by Vault Consulting, LLC, American Chemistry Council, U.S. Resin Production & Sales 2017 vs. 2016, March, 2018.

olefins/hydrogen. All data received were carefully evaluated before compiling the production-weighted average data sets used to generate results. Supporting background data were drawn from credible, widely used databases including the US LCI database, GREET, 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 off-gas 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 credit 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 HDPE resin and olefins.

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 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 HDPE resin 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. The material coproducts from HDPE resin production include isomers and off-spec and scrap material.

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).

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

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

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

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 mostly from plants in the United States with one HDPE plant in Canada. 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

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

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].

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.

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

[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 HDPE:

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 out system results into the following for HDPE:

- Cradle-to-incoming materials – includes the raw materials through the production of ethylene, cyclohexane, catalysts (metals and silica gel), and hydrogen
- HDPE resin production – is the gate-to-gate HDPE resin unit process and includes nitrogen production for use at the plant and fuel production and combustion for the unit process.

Tables and figures are provided for HDPE in each inventory and impact category section in this report. 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-HDPE and HDPE system are interchangeable). The phrase "gate-to-gate" is defined as including only the onsite process/fuels and no upstream or downstream material inputs and emissions.

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), which is the main input to HDPE resin.

The average total energy required to produce HDPE is 31.7 million Btu per 1,000 pounds of HDPE resin or 73.8 GJ per 1,000 kilograms of HDPE resin. Table 2 shows total energy demand for the life cycle of HDPE resin production. The HDPE resin production energy has been split out from the energy required for incoming materials, including olefins and hydrogen production, natural gas production and processing, and petroleum extraction and refining. Only 7.6 percent of the total energy is required to produce the HDPE resin itself. The remaining energy is used to create the incoming materials to the HDPE plant. Approximately two-thirds of the energy for HDPE resin production at the plant is required to create electricity.

Table 2. Total Energy Demand for HDPE Resin

	Basis: 1,000 pounds		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	MM Btu	***MM Btu***	***MM Btu***
Cradle-to-Incoming Materials	29.3	29.3	0.032
Virgin HDPE Resin Production	2.41	2.32	0.094
Total	**31.7**	**31.6**	**0.13**
	Basis: 1,000 kilograms		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	GJ	***GJ***	***GJ***
Cradle-to-Incoming Materials	68.2	68.1	0.075
Virgin HDPE Resin Production	5.61	5.39	0.22
Total	**73.8**	**73.5**	**0.29**
	Percentage		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	%	***%***	***%***
Cradle-to-Incoming Materials	92.4%	92.3%	0.1%
Virgin HDPE Resin Production	7.6%	7.3%	0.3%
Total	**100%**	**99.6%**	**0.4%**

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 the HDPE resin, 99.6 percent of the total energy comes from non-renewable sources. The renewable energy demand consists of landfill gas used for process energy in olefins production and electricity derived from renewable energy sources (primarily hydropower, as well as wind, solar, and other sources). Of the renewable energy (0.22 GJ/1000 kg) used at the HDPE resin plant, 99 percent comes from hydropower and other renewable sources (geothermal, solar, etc.) from electricity production used in the HDPE resin production.

The energy representing natural gas and petroleum used as raw material inputs for the production of ethylene used to produce HDPE resin are included in the cradle-to-incoming materials amounts in Table 2. The energy inherent in these raw materials are called material feedstock energy. Of the 73.8 GJ of energy for 1,000 kg of HDPE resin, 49.5 GJ is material feedstock energy. Figure 3 provides the breakdown of the percentage of total energy required for material feedstock energy versus the process and fuel energy amounts needed to produce the HDPE resin. Approximately 67 percent of the total energy is inherent energy in the natural gas and petroleum used as a feedstock to create ethylene, which in turn is used to create HDPE resin. Ninety percent of the feedstock sources for ethylene come from natural gas, while 10 percent of the feedstock sources come from oil.

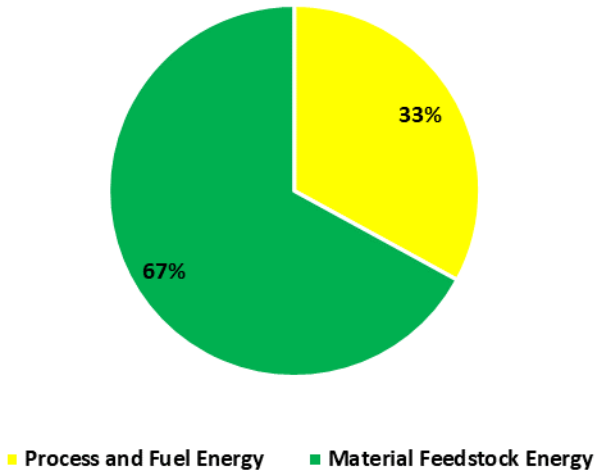

Figure 3. Process/Fuel and Material Feedstock Percentages for HDPE Resin

Energy Demand by Fuel Type

The total energy demand by fuel type for HDPE is shown in Table 3 and the percentage mix is shown in Figure 4. Natural gas and petroleum together make up almost 96 percent of the total energy used. As shown in Figure 3, this is partially due to the material feedstock energy used to create the olefins, which is the main input to HDPE resin. 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 HDPE resin in the following tables and figures represents the energy required for transportation of raw materials to HDPE manufacturers, the energy required to produce the HDPE resin, and the production of the fuels needed to manufacture the HDPE.

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

Of the results for HDPE resin production shown in Table 3 and Figure 4, almost 89 percent of the energy used (65.4 GJ/73.8 GJ) is from natural gas. At the HDPE resin plant, more than half of the energy used (3.14 GJ/5.6 GJ) comes from natural gas, with about a third of that amount combusted directly at the plant. Most of the remainder of the natural gas used by the HDPE plant is from creating electricity off-site. Petroleum comprises approximately 2 percent (0.12 GJ/5.6 GJ) of the fuel used for HDPE resin production at the plant; more than half of this petroleum is combusted to create electricity with the remaining mostly from transport of incoming materials. The coal use shown for the plant 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, while another third of the grid comes from natural gas and 20 percent from uranium. The hydropower, nuclear, and other energy are all used to create electricity, with the exception of a small amount of landfill gas used in the olefins production shown within other renewables.

Table 3. Energy Demand by Fuel Type for HDPE Resin

	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*
Cradle-to-Incoming Materials	29.3	26.8	2.29	0.12	0.081	0.0087	0.024
Virgin HDPE Resin Production	2.41	1.35	0.051	0.55	0.37	0.039	0.055
Total	**31.7**	**28.1**	**2.34**	**0.67**	**0.45**	**0.048**	**0.078**
	Basis: 1,000 kilograms						
	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
	GJ	*GJ*	*GJ*	*GJ*	*GJ*	*GJ*	*GJ*
Cradle-to-Incoming Materials	68.2	62.3	5.33	0.28	0.19	0.020	0.055
Virgin HDPE Resin Production	5.60	3.14	0.12	1.27	0.85	0.091	0.13
Total	**73.8**	**65.4**	**5.45**	**1.55**	**1.04**	**0.11**	**0.18**
	Percentage of Total						
	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
	%	*%*	*%*	*%*	*%*	*%*	*%*
Cradle-to-Incoming Materials	92.4%	84.4%	7.2%	0.4%	0.3%	0.03%	0.07%
Virgin HDPE Resin Production	7.6%	4.3%	0.2%	1.7%	1.2%	0.1%	0.17%
Total	**100%**	**88.7%**	**7.4%**	**2.1%**	**1.4%**	**0.2%**	**0.2%**

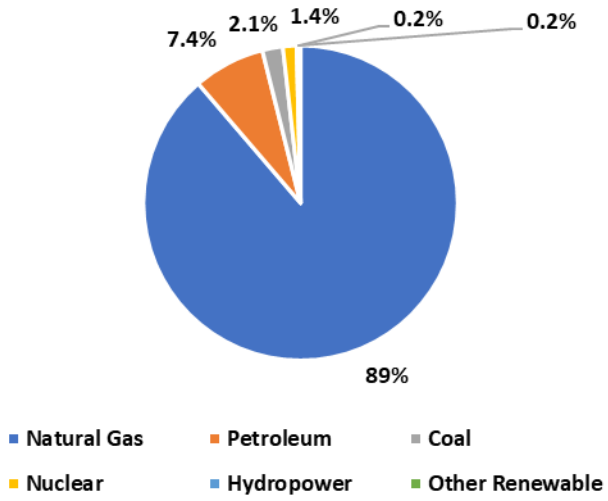

Figure 4. Percentage of Energy Separated by Fuel Type for HDPE Resin

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 HDPE (e.g., sludges and residues from chemical reactions and material processing steps, packaging, miscellaneous wastes)
- **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 HDPE resin are included in this analysis as no product is made from the material in the analysis boundaries.

The process solid waste, those wastes produced directly from the production of materials, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. Some wastes are recycled/reused and land applied but have not been included as solid wastes. The categories of disposal type 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 HDPE resin system are shown in Table 4 and Figure 5. The solid wastes have been separated into hazardous and non-hazardous waste categories, as well as by cradle-to-incoming materials and the HDPE plant. As shown in Figure 5, one-third of the total solid waste is created during the HDPE resin unit process. This comes mostly from fuel combusted with a small amount of process solid waste created during the HDPE production. The greatest amount of solid waste from the HDPE unit process comes from coal production and combustion used to create electricity for the HDPE resin plant. Only 3 percent of the total solid wastes are process wastes from the HDPE resin plant.

The remaining two-thirds of the solid waste comes from the production of incoming materials used to produce HDPE resin. Approximately 90 percent of the raw materials used to create ethylene are a product of natural gas processing, with the remaining 10 percent of those raw materials from crude oil refining products. The olefins plant process wastes make up over 10 percent of the total solid wastes.

Solid wastes are shown separated by hazardous and non-hazardous wastes in Table 4. 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. The process solid wastes from oil and natural gas were classified as non-hazardous due to exclusions found in RCRA hazardous wastes regulations or other EPA hazardous wastes regulations. No solid wastes were stated as hazardous in the data sources for oil and gas. Only 2.3 percent of the total solid wastes were considered hazardous wastes. Of that percentage, over 80 percent come from the incoming materials, with the remaining attributed to the HDPE unit process.

Table 4 also provides a breakout of the total solid wastes by the disposal fate. Of the hazardous waste, only 1 percent of it is landfilled; while 85 percent is incinerated without energy capture and almost 15 percent incinerated with energy capture. Focusing specifically on the non-hazardous solid waste produced, over 90 percent of the solid waste is landfilled, while 9 percent is incinerated, and a minute amount sent to waste-to-energy.

Table 4. Total Solid Wastes for HDPE Resin

	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*
Cradle-to-Incoming Materials	47.7	0	1.38	0.0031	1.38	6.0E-04	5.91	40.4	46.4
Virgin HDPE Resin Production	23.8	0.23	0.040	0.013	0.28	3.6E-03	0.072	23.4	23.5
Total	**71.5**	**0.23**	**1.42**	**0.016**	**1.67**	**4.2E-03**	**5.99**	**63.9**	**69.8**
	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*
Cradle-to-Incoming Materials	47.7	0	1.38	0.0031	1.38	6.0E-04	5.91	40.4	46.4
Virgin HDPE Resin Production	23.8	0.23	0.040	0.013	0.28	3.6E-03	0.072	23.4	23.5
Total	**71.5**	**0.23**	**1.42**	**0.016**	**1.67**	**4.2E-03**	**5.99**	**63.9**	**69.8**
	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
	%	*%*	*%*	*%*	*%*	*%*	*%*	*%*	*%*
Cradle-to-Incoming Materials	66.8%	0%	1.9%	0.004%	1.9%	0.001%	8.3%	56.6%	64.8%
Virgin HDPE Resin Production	33.2%	0.3%	0.1%	0.02%	0.4%	0.005%	0.1%	32.7%	32.8%
Total	**100%**	**0.3%**	**2.0%**	**0.02%**	**2.3%**	**0.006%**	**8.4%**	**89.3%**	**97.7%**

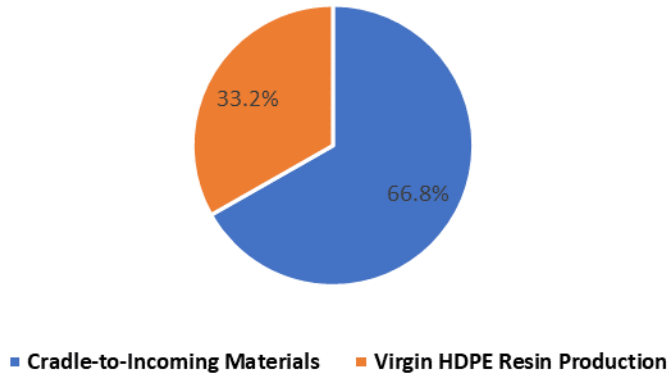

Figure 5. Percentage of Total Solid Wastes for HDPE Resin System

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 HDPE resin production are shown in Table 5 and Figure 6. A little more than a third of the consumption of water within the HDPE resin comes from the HDPE resin production, while the input materials required to produce the HDPE resin make up two-thirds. When looking at the individual unit processes, over 40 percent of the total is consumed at the olefins plant. The primary water consumption data for olefins 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 HDPE resin plant data also includes some plants that release water to a different watershed. The HDPE resin plant water consumption amount comprises about 17 percent of the total water consumption. Another large contributor for water consumption is the electricity used during all processes due to evaporative losses in the use of hydropower, which makes up over 20 percent of the total water consumption. Over 14 percent of the water consumed comes from the extraction of natural gas and petroleum necessary to create input materials to the olefins plant. The remaining water consumption comes from the processing of natural gas, refining of crude oil, and production of other input materials and fuels used.

Table 5. Water Consumption for HDPE Resin

	Total Water Consumption		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	Gallons	*Liters*	*%*
Cradle-to-Incoming Materials	630	5,254	64.5%
Virgin HDPE Resin Production	346	2,889	35.5%
Total	**976**	**8,143**	**100%**

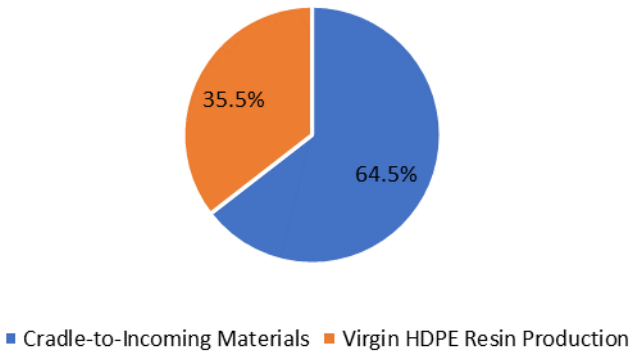

Figure 6. Water Consumption for HDPE Resin

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 and HDPE resin, 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[15] 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 plastic. It is the potential energy associated with the feedstock material, which is not combusted to create greenhouse gases.

Table 6 and Figure 7 show life cycle GWP results for the HDPE resin system. Of the total, 76 percent of the GWP are attributed to emissions from the incoming materials production, with the remaining GWP associated with the production of HDPE resin. The largest amount of the GWP is created by the production of ethylene, which accounts for 42 percent of the total GWP, which comes directly from the release of greenhouse gases at the olefins plant. A little more than 3 percent of the total GWP is created by the HDPE resin plants. Over 20 percent of the total GWP are emissions associated with fuel use and combustion of coal and natural gas in industrial and utility boilers. The natural gas extraction, processing and transport used as a material input to the olefins plant comprises 24 percent of the total GWP.

[15] 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.

Table 6. Global Warming Potential for HDPE Resin

	Global Warming Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CO2 eq	*kg CO2 eq*	*%*
Cradle-to-Incoming Materials	1,221	1,221	76%
Virgin HDPE Resin Production	390	390	24%
Total	**1,612**	**1,612**	**100%**

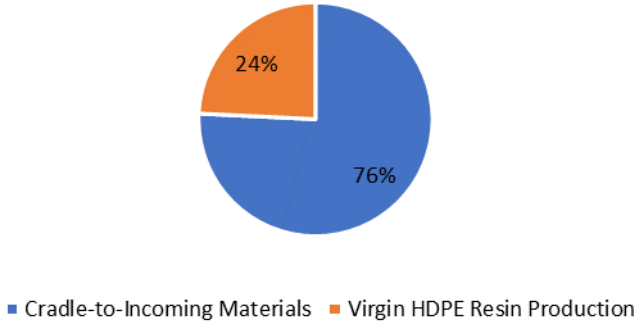

Figure 7. Global Warming Potential for HDPE Resin

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 damage to infrastructure. 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.[16,17]

Acidification impacts are typically dominated by fossil fuel combustion emissions, particularly sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Emissions from the extraction and processing of natural gas is a significant contributor to acidification impacts for the system. Also, emissions from combustion of fossil fuels, especially coal, to generate grid electricity impact the AP category.

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16 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.

17 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.

Table 7 shows total acidification potential (AP) results for the HDPE resin system. Results are shown graphically in Figure 8. The AP category indicates that 27 percent of the AP comes from HDPE resin production with the remaining 73 percent coming from the raw and intermediate material unit processes. As stated previously, much of the AP amount (24 percent) comes from the combustion of coal during the creation of electricity, which is used in all unit processes. Almost two-thirds of the AP (63 percent) comes from the extraction and processing of natural gas for materials and fuels, which is used to create 90 percent of the material inputs to the olefins plants. Only 4 percent of the AP results come from emissions released at the olefins plants, and less than 1 percent from the HDPE resin plants.

Table 7. Acidification Potential for HDPE Resin

	Acidification Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb SO2 eq	*kg SO2 eq*	*%*
Cradle-to-Incoming Materials	3.82	3.82	73%
Virgin HDPE Resin Production	1.40	1.40	27%
Total	**5.22**	**5.22**	**100%**

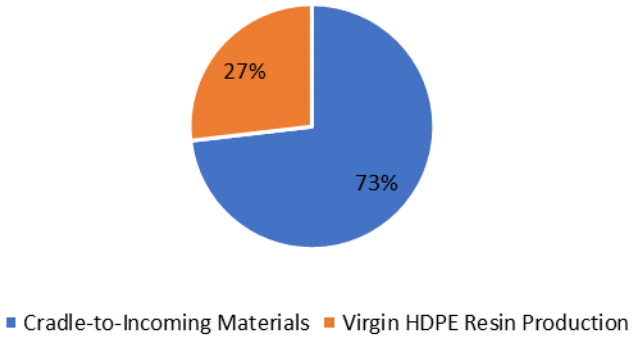

Figure 8. Acidification Potential for HDPE Resin

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.[18] The TRACI characterization factors for

[18] 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.

eutrophication are the product of a nutrient factor and a transport factor.[19] The nutrient factor is based on the amount of plant growth caused by each pollutant, while the transport 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 HDPE resin are shown in Table 8 and illustrated in Figure 9. The largest portion, over 87 percent, of the EP results come from the raw and intermediate materials used to create HDPE resin. Within this amount, the extraction of natural gas for materials and fuels releases 68 percent of the emissions related to the EP impact. The olefins plant process emissions comprise over 12 percent of the EP impact results. The HDPE resin production generates 13 percent of the EP impact, with two-thirds of that percentage representing the combustion of coal and natural gas for electricity. Only 1 percent of the total EP impact comes from process emissions released at the HDPE plant.

Table 8. Eutrophication Potential for HDPE Resin

	Eutrophication Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb N eq	*kg N eq*	*%*
Cradle-to-Incoming Materials	0.23	0.23	87%
Virgin HDPE Resin Production	0.035	0.035	13%
Total	**0.26**	**0.26**	**100%**

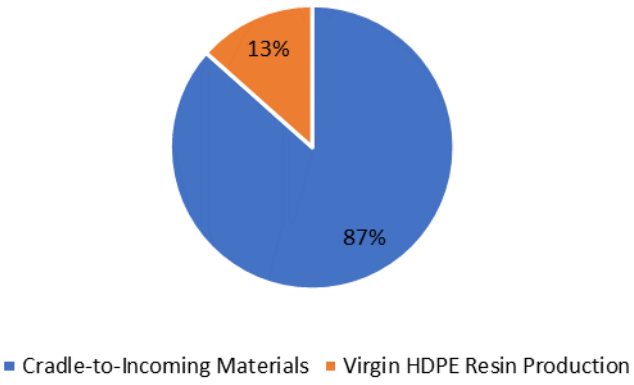

Figure 9. Eutrophication Potential for HDPE Resin

[19] 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.

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. For the HDPE resin system, 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 9 shows total ODP results for the HDPE resin system, which are also shown graphically in Figure 10. Ozone depletion results for the HDPE resin system are dominated by the crude oil extraction and refining system, contributing almost 99 percent of the total ozone depletion impacts. One percent of the total ODP does come from the mining and processing of the titanium used in the Ziegler-Natta catalyst used in the slurry loop reactor. The amount of the ODP shown as HDPE resin production is from the production of petroleum-based fuels used within the plant. No emissions impacting ODP are released at the ethylene or HDPE plants.

Table 9. Ozone Depletion Potential for HDPE Resin

	Ozone Depletion Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CFC-11 eq	*kg CFC-11 eq*	*%*
Cradle-to-Incoming Materials	1.2E-06	1.2E-06	97.6%
Virgin HDPE Resin Production	3.0E-08	3.0E-08	2.4%
Total	**1.2E-06**	**1.2E-06**	**100%**

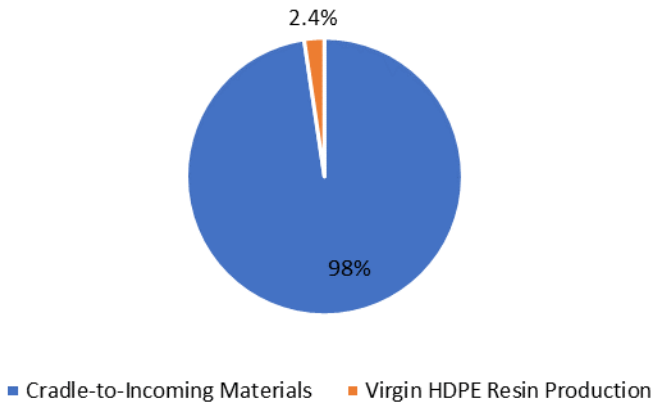

Figure 10. Ozone Depletion Potential for HDPE Resin

PHOTOCHEMICAL SMOG FORMATION

The photochemical smog formation (historically photochemical oxidant creation potential) (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.[20] 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 97 percent of the smog formation emissions, with VOCs consisting of another 2 percent. Natural gas extraction and processing are where the largest amounts of these emissions are released and so dominate the POCP category, making up almost 75 percent of the total results.

Smog formation potential results for HDPE resin are displayed in Table 10 and illustrated in Figure 11. Approximately 85% of the POCP impact results comes from the raw and intermediate materials (cradle-to-olefins). The olefins plant releases 5 percent of the total emissions resulting the POCP. Much of the remainder (79 percent) of the total POCP impact results within the cradle-to-incoming materials amount are from the production and combustion of natural gas for both materials and fuels. Smaller amounts are also created from the combustion of coal and the extraction of oil.

The remaining 15 percent of the POCP impact results is released from the HDPE resin production process. Almost 70 percent of the POCP from the HDPE resin plant comes from the use of electricity in the plant, which includes the combustion of natural gas and coal at power plants and cogeneration plants. Only 5 percent of the POCP from the HDPE resin plant are released at the HDPE resin plant as process emissions.

Table 10. Photochemical Smog Formation Potential for HDPE Resin

	Photochemical Smog Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb O3 eq	*kg O3 eq*	*%*
Cradle-to-Incoming Materials	110	110	85%
Virgin HDPE Resin Production	18.7	18.7	15%
Total	**129**	**129**	**100%**

[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.

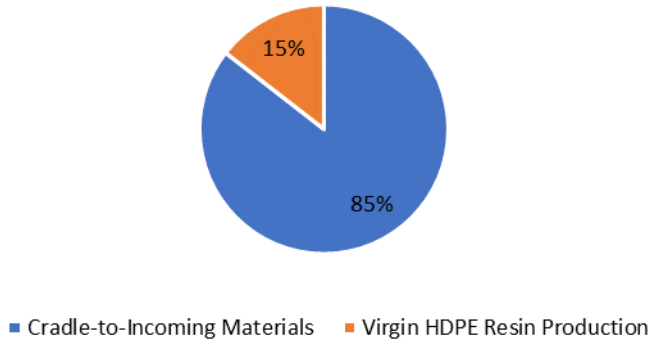

Figure 11. Photochemical Smog Formation Potential for HDPE Resin

COMPARISON OF 2020 AND 2011 LCI AND LCIA RESULTS

This section provides a comparison of life cycle inventory and impact assessment category results that were included in the original virgin HDPE system[21] with the current update. These categories include total energy, non-renewable energy, renewable energy, total solid waste, and global warming potential. No comparisons are available for water consumption, solid waste broken out as hazardous and non-hazardous categories, acidification potential, eutrophication potential, photochemical smog formation, or ozone depletion potential. These categories were not included in the original study.

Table 11 shows the comparable LCI and LCIA categories for the 2011 and 2020 in both English and SI units and includes the percent change from the original results for each category. The percent change equals the difference of the two amounts divided by the 2011 original result. From the results, a decrease is seen for the non-renewable and total energy amounts, as well as the total solid waste and global warming potential. Only the renewable energy amounts are higher than the previous analysis from 2011. An increase in the use of renewable energy is considered a positive change, as the non-renewable energy decreased. Comparisons of these results have been analyzed in this section focusing on the main differences causing the decrease/increase in each category.

Broadly, results differences between the two averaged datasets are in part due to the use of additional or different companies and manufacturing plants when replacing the ethylene and HDPE primary data. Overall, the number of companies providing HDPE data increased from 3 to 5 and number of plants increased from 5 to 10. The new HDPE average would be considered much more robust that the 2011 HDPE average. Each plant producing the same resin or chemical varies by the amounts of input materials used, fuel types and amounts used, amounts of emissions released, etc. The amalgamation of these changes lead to differences affecting the results. Data were collected for HDPE resin and ethylene for the years 2015-2016. For ethylene and HDPE, some of the same plants were included; however,

[21] American Chemistry Council, Plastics Division, Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors. Prepared by Franklin Associates, A Division of ERG. August, 2011.

many of the plants in the averages were not included in the original data collection in 2004-2006. More plants participated in the data collection for this update for the ethylene resin as well. Another broad difference for the results stem from the decrease in coal use/increase in natural gas & renewable fuels in the national electricity grids for the original and updated results.

Table 11. Comparison of 2011 and 2020 LCI and LCIA Results for Virgin HDPE Resin

	1000 pounds of Virgin High-Density Polyethylene Resin				
	LCI Results				*LCIA Results*
	Total Energy	Non-Renewable Energy	Renewable Energy	Total Solid Waste*	Global Warming
	MM Btu	*MM Btu*	*MM Btu*	*lb*	*lb CO_2 eq*
HDPE 2020	31.7	31.6	0.13	69.8	1,612
HDPE 2011	33.7	33.5	0.11	77.1	1,897
	1000 kilograms of Virgin High-Density Polyethylene Resin				
	LCI Results				*LCIA Results*
	Total Energy	Non-Renewable Energy	Renewable Energy	Total Solid Waste*	Global Warming
	GJ	*GJ*	*GJ*	*kg*	*kg CO_2 eq*
HDPE 2020	73.8	73.5	0.29	69.8	1,612
HDPE 2011	78.3	78.0	0.26	77.1	1,897
Percent Change	-6%	-6%	13%	-9%	-15%

*Total Solid Waste excludes hazardous solid waste for 2020 as this category was not included as Solid Waste in 2011.

ENERGY COMPARISON

Overall, the total energy for HDPE resin has decreased 4.5 GJ on a 1,000 kg basis (2.0 MMBtu/1,000 lb). This is a 6 percent decrease in total energy as compared to the original results. When comparing the HDPE resin unit process average energy data, there were small decreases when comparing data from companies that collected data for both studies. However, 5 new plants were included in the average. The addition of new plants into the analysis affected the change in energy. Figure 12 provides a graphical perspective of the unit processes associated with this energy decrease from the original energy amounts.

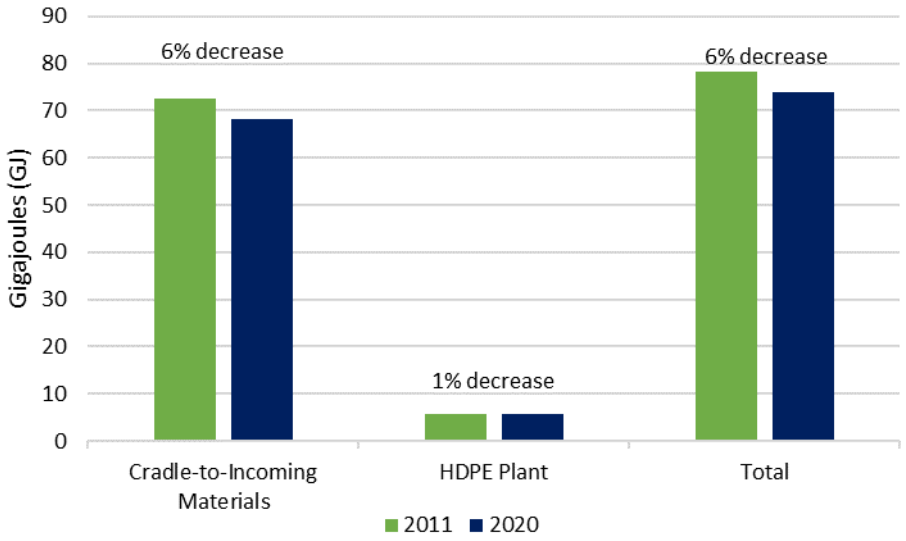

Figure 12. Decrease in Energy by Stage per 1,000 kg (GJ)

The energy of material resource, which pertains to the amount of inherent energy from the raw materials, decreased by 0.7 GJ per 1,000 kg of HDPE resin. The olefins feedstock use of approximately 90 percent coming from natural gas and 10 percent from oil is an increase in natural gas use from the 2011 report, which used an 82/18 split of natural gas to oil. The transport energy continues to make up approximately 1 percent, with the remaining energy coming from the processes. Most of the changes overall come from the process energy in the olefins plant. The energy specific to the HDPE plant remained somewhat constant with a small decrease of 1 percent of its previous total. This can be accounted for due to the differences in plants providing data, the number of which doubled. The decrease in total energy was made greater by the decrease in energy (4.5 GJ/1000 kg of HDPE resin) shown in the cradle-to-incoming materials processes. The olefins unit process energy did decrease from the original data collection. Also, the overall energy use for both the oil and natural gas extraction and processing/refining decreased by small amounts.

The difference in renewable energy is a 13 percent increase from the original results. It should be noted that the renewable energy makes up less than one percent of the total energy. This change would include the use of landfill gas (considered renewable) and the differences in the electrical grid (small increases in hydropower and other renewable resources for energy).

SOLID WASTE COMPARISON

When compared to the 2011 HDPE resin total solid waste amount, the current HDPE resin study creates 7 kg/1000 kg HDPE resin less solid waste, which is a 9 percent decrease. Some of this decrease is due to the differences in olefin and HDPE plant data collected between the

2011 and 2020 reports, as well as their weighting within the average which uses production amounts. Figure 13 provides a visual of the total solid waste amount split out by the HDPE unit process and cradle-to-incoming materials. A larger decrease occurs in the incoming materials production, which includes olefins, while a smaller increase is shown for the HDPE plants. The HDPE plant process solid waste did increase due to the inclusion of more plants than in the 2011 study. When comparing the companies that provided data for both studies, there was a variance by company with some companies having increased solid waste, while others had decreased. Another reason that solid waste decreased overall is the use of less coal in the electricity grid, which creates ash. The use of more of the national electricity grid versus cogeneration for the HDPE process increased compared to 2011, but this was due to the inclusion of more companies in the average. The olefins plant electricity use decreased overall, while the split of cogeneration and grid electricity remained very close to the earlier analysis. Process solid wastes from the natural gas and crude oil production also decreased by small amounts.

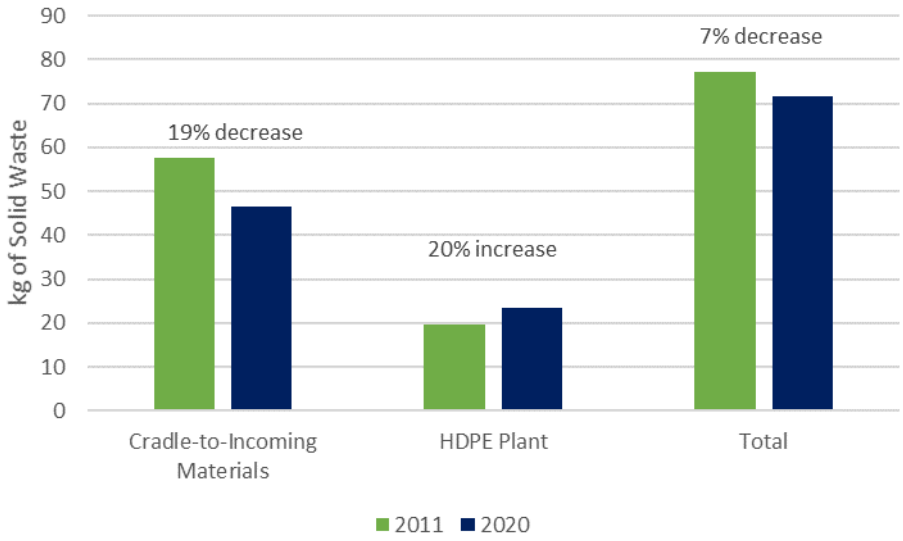

Figure 13. Decrease in Solid Waste Weight by Unit Process (kg Per 1,000 kg)

GLOBAL WARMING POTENTIAL COMPARISON

The global warming potential decreased by 285 kg CO_2 equivalents/1000 kg HDPE resin, or 15 percent compared to the 2011 HDPE resin GWP result. Figure 14 displays a column chart with the HDPE resin and cradle-to-incoming materials results that makeup the total decrease when comparing the 2011 and 2020 GWP results. The cradle-to-incoming materials decrease follows the trend shown in total energy, since much of the greenhouse gases are created from fuel production. The GWP for the HDPE resin plant increased. Some of this increase is due to decrease in using cogeneration electricity to increased grid electricity in the average, due to the additional plants providing data. Coal production and combustion

releases higher amounts of greenhouse gases compared to natural gas production and combustion. Another reason the HDPE resin GWP increased is the inclusion of flare emissions that were not included in 2011. Flare emissions are included as a mix of process and fuel emissions so as to capture any possible greenhouse gases released from the substances being flared. The decrease in GWP for Olefins comes from decreases in energy use for the raw materials and for the olefins plant.

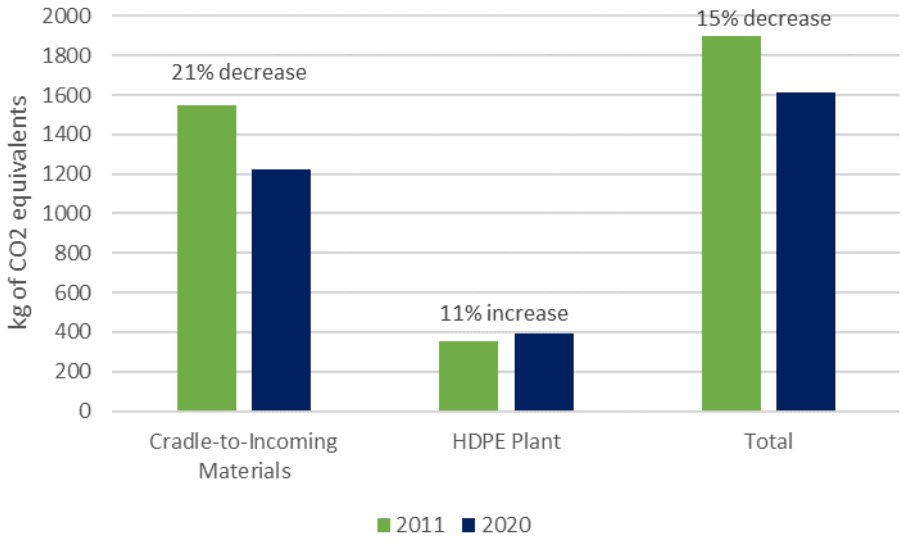

Figure 14. Decrease in Global Warming Potential by Unit Process (kg of CO2 eq. per 1,000 kg)

APPENDIX: HIGH-DENSITY POLYETHYLENE (HDPE) MANUFACTURE

This appendix discusses the manufacture of HDPE, which is used for many plastics products, including the production of bottles, household and industrial packaging, and pipes. The captured HDPE production amount is approximately 63 percent of the HDPE production in the U.S. in 2016 (American Chemistry Council, 2018). The flow diagram of processes included for HDPE resin is provided in Figure 15.

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:

- Hydrogen from Steam Cracking
- High-density Polyethylene (HDPE) Production

LCI data for olefins/hydrogen and HDPE production were collected for this update to the U.S. LCI plastics database by member companies of the American Chemistry Council. Secondary data was used for crude oil extraction and refining and natural gas production and processing, cyclohexane and nitrogen. Results and LCI data for the production of olefins, oil, and natural gas can be found in the report, ***Cradle-to-Gate Life Cycle Analysis of Olefins***. LCI data for ancillary input materials, cyclohexane and nitrogen, were adapted from the ecoinvent 3 database. These datasets are not available due to confidentiality issues of that database. The adaptations included the use of the US electricity grid and US transportation.

HYDROGEN PRODUCTION FROM STEAM CRACKING

This analysis uses the hydrogen production from 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, hydrogen can be manufactured by a number of technologies. However, after reviewing the transport data of incoming hydrogen, it is likely that many of the HDPE producers are purchasing hydrogen from steam crackers within their area. This analysis only uses steam cracking as the source for hydrogen. No additional energy or emissions have been added for the separation/purification of the hydrogen from the steam cracker. The amounts of incoming hydrogen to HDPE are small, and so the results are not expected to be low by any significant amount.

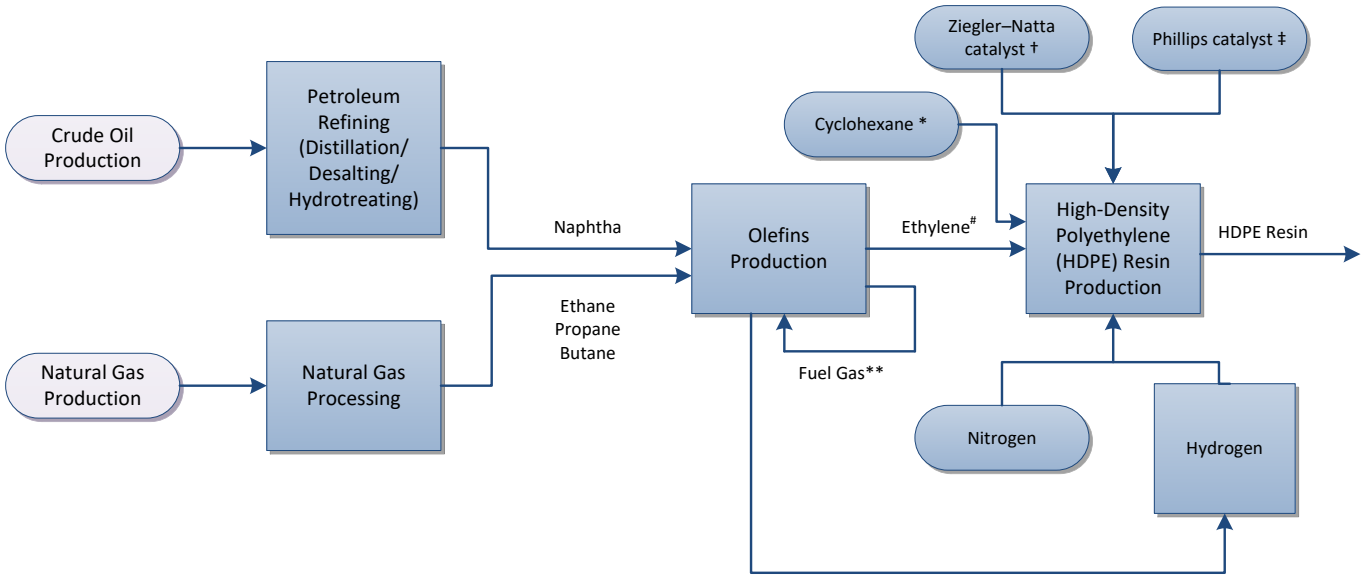

Figure 15. Flow diagram for the Production of High-Density Polyethylene (HDPE).

* Cyclohexane and nitrogen data are from ecoinvent and are adapted to U.S. conditions. Both inputs are used as ancillary materials.

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

Represents ethylene production and butene, hexene-1, isobutane, and isopentane production, which use ethylene as a surrogate.

† Modeled as the included titanium metal portion of catalyst only.

‡ Modeled as the included chromium metal and silica gel (SiO2) portion of catalyst only.

Typical production of olefins 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 off-gas is produced from the raw materials entering. A portion of this off-gas 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 off-gas 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 hydrogen. All companies provided data for the year 2015. A weighted average was calculated for hydrogen from the data collected and used to develop the LCA model. Propylene, ethylene, pyrolysis gasoline and butadiene are among the coproducts of hydrogen production from steam cracking, 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.

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 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 LCI data and provided questions as necessary.

Table 12 shows the averaged energy and emissions data for the production of 1,000 pounds and 1,000 kilograms of hydrogen. As a mass basis was used for the steam cracking unit process allocation, the differences in the individual olefins and hydrogen 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.

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.

Table 12. LCI Data for the Production of Hydrogen from Steam Cracking

	1,000 lb		1,000 kg		
Material Inputs (1)					
Refined Petroleum Products	81	lb	81	kg	
(65% naphtha, 35% refinery gases)					
Processesed Natural Gas	884	lb	884	kg	
(59% ethane, 38% propane, 3% butane)					
Internal off-gas (2)					
From oil	18.0	lb	18.0	kg	
From natural gas	196	lb	196	kg	
Energy					
Process Energy					
Electricity from grid	8.16	kWh	18.0	kWh	
Electricity from cogen	14.5	kWh	32.0	kWh	
Natural gas	1,746	ft^3	109	m^3	
Fuel Gas	1,746	ft^3	109	m^3	
Landfill gas	14.1	ft^3	0.88	m^3	
Avoided Energy					
Oil sold as co-product	0.046	gal	0.38	l	
Recovered energy from exported steam	336	ft^3	21.0	m^3	
Off-gas sold	320	ft^3	20.0	m^3	
Transportation Energy					
Barge	33.6	ton·mi	108	tonne·km	
Pipeline -refinery products	0.25	ton·mi	0.80	tonne·km	
Pipeline -natural gas products	203	ton·mi	652	tonne·km	
Environmental Emissions					
Atmospheric Emissions					
Particulates, unspecified	0.010	lb	0.010	kg	*
Particulates, < 2.5 um	0.010	lb	0.010	kg	
Particulates, > 2.5 um, and < 10um	0.0030	lb	0.0030	kg	
Nitrogen oxides	0.26	lb	0.26	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	0.025	lb	0.025	kg	
Carbon dioxide, fossil	640	lb	640	kg	
Methane, fossil	0.10	lb	0.10	kg	
Nitrous oxide	0.29	lb	0.29	kg	
Carbon monoxide	0.33	lb	0.33	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	*

Table 12. LCI Data for the Production of Hydrogen from Steam Cracking (Continued)

	1,000 lb	1,000 kg	
Environmental Emissions			
Waterborne Releases			
Benzene	0.010 lb	0.010 kg	*
BOD5, Biological Oxygen Demand	0.0024 lb	0.0024 kg	
COD, Chemical Oxygen Demand	0.13 lb	0.13 kg	
Benzene, ethyl-	0.0010 lb	0.0010 kg	*
Phenol	1.0E-05 lb	1.0E-05 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	0.0001 lb	1.0E-04 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	0.44 lb	0.44 kg	
Solid waste, process to incineration	8.67 lb	8.67 kg	
Solid waste, process to waste-to-energy incineration	9.7E-04 lb	9.7E-04 kg	
Solid Waste, sold for recycling or reuse	0.36 lb	0.36 kg	
Hazardous waste to landfill	0.0017 lb	0.0017 kg	
Hazardous waste to incineration	2.22 lb	2.22 kg	

Table 12. LCI Data for the Production of Hydrogen from Steam Cracking (Continued)

	1,000 lb	1,000 kg
Water Consumption	448 gal	3,740 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

HIGH-DENSITY POLYETHYLENE (HDPE) PRODUCTION

The main raw materials for HDPE production are ethylene with small amounts of octene, hexene and butene. Olefins can be produced from either a refinery of petroleum or a processing plant of natural gas. Information on the production of these can be found in the olefins appendix in the report, ***Cradle-to-Gate Life Cycle Analysis of Olefins***.

Commonly in North America, high-density polyethylene (HDPE) is produced by the polymerization of mainly ethylene in low pressure reactors. The three main reactor types used are gas-phase, slurry loop, and solution reactors. Hybrid technologies of slurry and gas phase are also available and used. The solution reactor was not stated as their representative technology by any of the data providers and is used less frequently than the other technologies.

Normally a combination of Phillips, Ziegler-Natta and/or metallocene catalysts are required during the process. The metal mining and processing for titanium (ZN catalyst) and chromium and silica gel used in the Phillips catalyst were included in the models.

The gas-phase reactor is able to produce both HDPE and LLDPE in the same reactor and is the leading technology for new plants since the 1980s (Chatterjee, 2017). This is usually done in a fluidized bed reactor. Here a gas stream containing monomer recycles through the bed of polymer. Catalyst activators, comonomers, and hydrogen are fed through the bed. The reaction temperatures range from 70 to 120 C and at a pressure of 20 to 30 bar. Polymer is discharged occasionally into a tank system to separate gas from solid.

The slurry loop reactor is a continuous stirred-tank reactor. In this technology, the slurry includes undissolved polymer as well as diluent, ethylene, comonomer, catalyst(s), and hydrogen. These components are continuously supplied through the loop. Some of the slurry, containing high amounts of solid, are discharged and the solids are separated while the

remaining fluid is recycled back into the reactor. Chrome, Ziegler-Natta, and metallocene catalysts can be used in this technology.

LCI data for the production of HDPE resin were collected from five producers (ten plants) in North America –the United States and Canada. Four companies provided data for the year 2015 and one company provided data for the year 2016. A weighted average was calculated from the data collected and used to develop the LCA model. The captured HDPE resin production amount is approximately 63 percent (American Chemistry Council, 2018) of the HDPE resin production in the U.S. in 2015. Only small amounts of isomers and off-spec/scrap PE are coproducts of HDPE resin production, and a mass basis was used to allocate the credit for the coproducts.

HDPE resin producers from the United States and Canada provided data from their facilities using technology ranging from old to average to state-of-the-art. This is possibly due to the technology itself being older (1960s), while some plants have considered updates to plants and catalysts/processes as state-of-the-art. The slurry-loop reactor is the older of the two types of reactor used to produce HDPE resin. Many of the plants producing HDPE resin have hybrids using both types of reactor.

Primary data were collected from HDPE manufacturers from the year 2015 and 2016. 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 or 2016 was a representative year for HDPE production in North America.

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 13 shows the averaged energy and emissions data for the production of 1,000 pounds and 1,000 kilograms of HDPE resin. 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.

Table 13. LCI Data for the Production of High-Density Polyethylene (HDPE)

	1,000 lb		1,000 kg		
Material Inputs (1)					
Ethylene	983	lb	983	kg	(1)
Hydrogen	1.80	lb	1.80	kg	
Nitrogen	10.2	lb	10.2	kg	
Cyclohexane	0.48	lb	0.48	kg	
Titanium (from catalyst)	3.8E-03	lb	3.8E-03	kg	
Chromium (from catalyst)	2.2E-03	lb	2.2E-03	kg	
Silica gel (SiO2 from catalyst)	0.22	lb	0.22	kg	
Energy					
Process Energy					
Electricity from grid	140	kWh	309	kWh	
Electricity from cogen	37	kWh	82	kWh	
Natural gas	452	ft^3	28.2	m^3	
Residual Oil	1.3E-04	gal	1.1E-06	m^3	
Transportation Energy					
Truck	0.011	ton·mi	0.035	tonne·km	
Rail	1.40	ton·mi	4.51	tonne·km	
Barge	0.80	ton·mi	2.59	tonne·km	
Pipeline -Natural gas	6.74	ton·mi	21.7	tonne·km	

Table 13. LCI Data for the Production of High-Density Polyethylene (HDPE) (Continued)

	1,000 lb	1,000 kg	
Environmental Emissions			
Atmospheric Emissions			
Particulates, unspecified	0.0036 lb	0.0036 kg	
Particulates, < 2.5 um	0.0069 lb	0.0069 kg	
Particulates, > 2.5 um, and < 10um	0.017 lb	0.017 kg	
Nitrogen oxides	0.040 lb	0.040 kg	
Sulfur oxides	0.0016 lb	0.0016 kg	
Carbon dioxide, fossil	37.0 lb	37.0 kg	
Methane	0.64 lb	0.64 kg	
Nitrous oxide	3.2E-05 lb	3.2E-05 kg	
Carbon monoxide	0.17 lb	0.17 kg	
NMHC, non-methane hydrocarbons	0.062 lb	0.062 kg	
Hydrocarbons, unspecified	0.0056 lb	0.0056 kg	
1-Butene	0.0010 lb	0.0010 kg	*
Cyclohexane	0.010 lb	0.010 kg	*
Ethylene	0.13 lb	0.13 kg	
Biphenyl	1.0E-04 lb	1.0E-04 kg	*
Pentane	1.0E-04 lb	1.0E-04 kg	*
Naphthalene	1.0E-08 lb	1.0E-08 kg	*
1-Octene	1.0E-04 lb	1.0E-04 kg	*
2-Methyl pentane	1.0E-04 lb	1.0E-04 kg	*
Diphenyl Oxide	1.0E-04 lb	1.0E-04 kg	*
1-Hexene	0.010 lb	0.010 kg	*
Isopentane	0.0010 lb	0.0010 kg	*
Isopropyl Alcohol	0.0010 lb	0.0010 kg	*
Propylene	0.0010 lb	0.0010 kg	*
Ethane	0.0010 lb	0.0010 kg	*
n-Butane	1.0E-04 lb	1.0E-04 kg	*
Isobutane	0.010 lb	0.010 kg	*
Hexane	0.0010 lb	0.0010 kg	*
Decane	1.0E-04 lb	1.0E-04 kg	*
Dodecane	1.0E-04 lb	1.0E-04 kg	*
Heptane	1.0E-04 lb	1.0E-04 kg	*
Isobutylene	1.0E-04 lb	1.0E-04 kg	*
Octane	0.0010 lb	0.0010 kg	*
Propane	1.0E-04 lb	1.0E-04 kg	*

Table 13. LCI Data for the Production of High-Density Polyethylene (HDPE) (Continued)

	1,000 lb		1,000 kg		
Waterborne Releases					
Fluorides	1.0E-06	lb	1.0E-06	kg	*
Dissolved Solids	0.10	lb	0.10	kg	*
BOD	0.0051	lb	0.0051	kg	
COD	0.010	lb	0.010	kg	*
Phenolics	1.0E-06	lb	1.0E-06	kg	*
Sulfides	1.0E-05	lb	1.0E-05	kg	
Oil & Grease	0.0035	lb	0.0035	kg	
Suspended Solids	0.035	lb	0.035	kg	
Cyanide	1.0E-06	lb	1.0E-06	kg	*
Chromium	1.0E-05	lb	1.0E-05	kg	*
Iron	0.0010	lb	0.0010	kg	*
Aluminum	0.0017	lb	0.0017	kg	
Nickel	1.0E-06	lb	1.0E-06	kg	*
Mercury	1.0E-09	lb	1.0E-09	kg	*
Lead	1.0E-06	lb	1.0E-06	kg	*
Phosphates	1.0E-07	lb	1.0E-07	kg	*
Zinc	7.4E-05	lb	7.4E-05	kg	
Ammonia	1.0E-07	lb	1.0E-07	kg	*
DOC	0.10	lb	0.10	kg	*
Phosphorous	1.0E-04	lb	1.0E-04	kg	*
Toluene	1.0E-06	lb	1.0E-06	kg	*
TOC	0.010	lb	0.010	kg	*
Arsenic	1.0E-05	lb	1.0E-05	kg	*
Copper	1.0E-06	lb	1.0E-06	kg	*
Solid Wastes					
Solid waste, process to landfill	0.38	lb	0.38	kg	
Solid Waste, sold for recycling or reuse	13.3	lb	13.3	kg	
Solid waste, process to incineration	0.072	lb	0.072	kg	
Solid waste, process to waste-to-energy	0.0036	lb	0.0036	kg	
Hazardous waste to landfill	0.013	lb	0.013	kg	
Hazardous waste to incineration	0.040	lb	0.040	kg	
Hazardous waste to WTE	0.23	lb	0.23	kg	
Hazardous waste, sold for recycling or reuse	0.0015	lb	0.0015	kg	
Water Consumption	171	gal	1,430	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) Ethylene production accounts for 953 lb/1,000 lb HDPE while the remainder of the amount is from butene, hexene-1, isobutane, and isopentane production which use ethylene as a surrogate.

Source: Primary Data, 2020

REFERENCES

American Chemistry Council (2018), Calculations using Plastics Industry Producers' Statistics Group (PIPS), as compiled by Vault Consulting, LLC, American Chemistry Council, U.S. Resin Production & Sales 2017 vs. 2016, March, 2018.

Chatterjee, Ananda, and Mark A. Spalding (Eds.) (2017). Handbook of Industrial Polyethylene and Technology. Wiley.

Primary Data (2018) Primary data from 2015 collected from 3 olefins producers by Franklin Associates. 2017-2018

Primary Data (2020). Primary data from 2015-2016 collected from 5 HDPE producers by Franklin Associates. 2017-2020.