CRADLE-TO-GATE LIFE CYCLE ANALYSIS OF LOW-DENSITY POLYETHYLENE (LDPE) RESIN

Final Report

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PREFACE

This life cycle assessment of LDPE 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.

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 and Keith Christman of ACC in leading this project. Also acknowledged are the following companies: Chevron Phillips Chemical Corporation, ExxonMobil Corporation, NOVA Chemical Corporation, and the Dow Chemical Company, who graciously provided primary Life Cycle Inventory data for LDPE production. Their effort in collecting data has added considerably to the quality of this LCA report.

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

April, 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
IPCC	INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
ISO	INTERNATIONAL ORGANIZATION FOR STANDARDIZATION
LCA	LIFE CYCLE ASSESSMENT
LCI	LIFE CYCLE INVENTORY
LCIA	LIFE CYCLE IMPACT ASSESSMENT
LDPE	LOW-DENSITY POLYETHYLENE
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 VLOATILE ORGANIC COMPOUNDS
NREL	NATIONAL RENEWABLE ENERGY LABORATORY
ODP	OZONE DEPLETION POTENTIAL
POCP	PHOTOCHEMICAL SMOG FORMATION
RCRA	RESOURCE CONSERVATION AND RECOVERY ACT
SI	INTERNATIONAL SYSTEM OF UNITS
TRACI	TOOL FOR THE REDUCTION AND ASSESSMENT OF CHEMICAL AND OTHER ENVIRONMENTAL IMPACTS
TRI	TOXIC RELEASE INVENTORY
WTE	WASTE-TO-ENERGY INCINERATION

CRADLE-TO-GATE LIFE CYCLE ASSESSMENT OF LOW-DENSITY POLYETHYLENE (LDPE)

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 Low-density Polyethylene (LDPE) resin, which is used to create a variety of films and packaging 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.

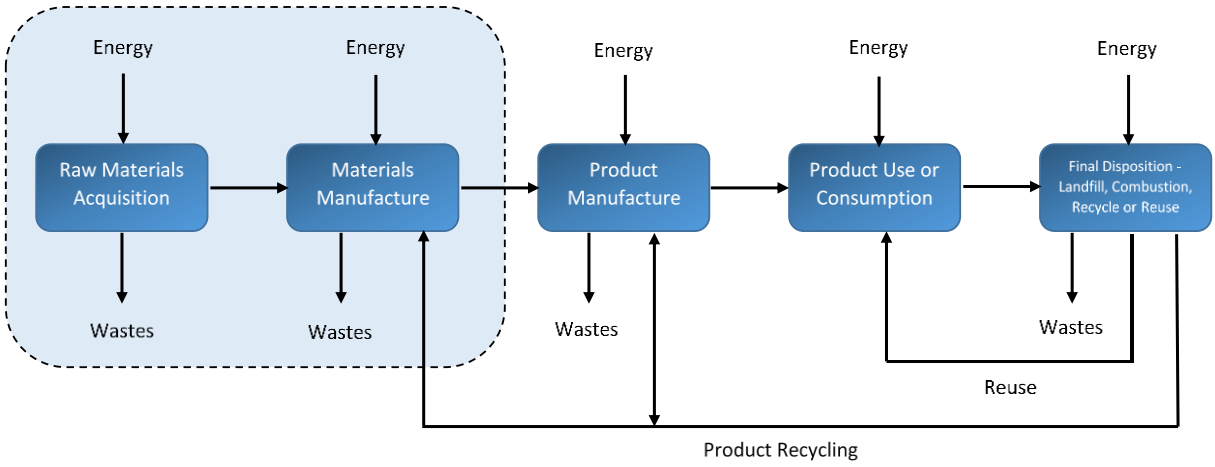

Figure 1. General materials flow for "cradle-to-grave" analysis of a product system. The dashed box indicates the boundaries of this analysis.

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 LDPE resin. It is considered a cradle-to-gate boundary system because this analysis ends with the LDPE resin production. The system boundaries stop at the LDPE 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 films, 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 LDPE 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.*** 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.

[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.

STUDY GOAL AND INTENDED USE

The purpose of this LCA is to document the LCI data and then evaluate the environmental profile of LDPE 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 LDPE resin and
- to provide information about the environmental burdens associated with the production of LDPE resin. The LCA results for LDPE production can be used as a benchmark for evaluating future updated LDPE 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 LDPE resin is its forming into various products, for example, trash liners and other films, flexible parts or plastic lumber. As the study boundary concludes at the LDPE 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 LDPE 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 LDPE 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
- LDPE resin manufacture, including incoming transportation for each material.

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

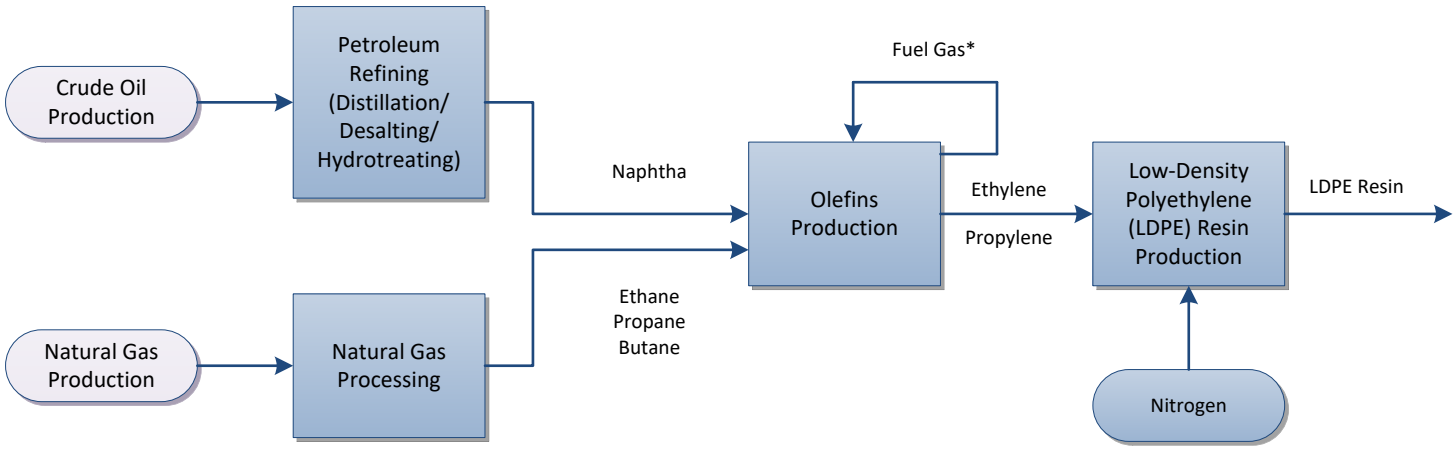

Figure 2. Flow diagram for the Production of Low-Density Polyethylene (LDPE).
*Fuel gas used for energy is created from off-gas produced in the process.

Technological Scope – High Pressure Reactors

The LDPE resin is commonly polymerized in high pressure reactors. This is the standard technology for LDPE resin production. The two reactor types used are autoclaves and tubular reactors. Generally, tubular reactors operate at a higher average ethylene conversion than autoclave reactors. The polymerization mechanism is either free-radical, using peroxide initiators, or ionic polymerization, using Ziegler catalyst.

All data providers used the high pressure technology and either the tubular or autoclave reactors with either peroxide initiators or a Ziegler catalyst.

Temporal and Geographic Scope

For the LDPE resin primary data, companies were requested to provide data for the year 2015, the most recent full year of LDPE 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. Two companies provided data for the year 2015, and two companies provided data for the year 2016. After reviewing individual company data in comparison to the average, each manufacturer verified data from 2015-2016 was representative of an average year for LDPE resin production at their company.

The geographic scope of the analysis is the manufacture of LDPE resin in North America. All LDPE 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. The U.S. electricity grid from 2016 was taken from information in Emissions & Generation Resource Integrated Database (eGRID) 2016 database.

Exclusions from the Scope

The following are not included in the study:

- **Miscellaneous materials and additives.** Selected materials such as catalysts, pigments, ancillary materials, or other additives which total less than one percent by weight of the net process inputs are typically not included in assessments. Omitting miscellaneous materials and additives keeps the scope of the study focused. It is possible that production of some substances used in small amounts may be energy and resource intensive or may release toxic emissions; however, the impacts would have to be very large in proportion to their mass in order to significantly affect overall results and conclusions. For this study, no use of resource-intensive or high-toxicity chemicals or additives was identified. Therefore, the results for the resin are not expected to be understated by any significant amount due to substances that may be used in small amounts.
- **Capital equipment, facilities, and infrastructure.** The energy and wastes associated with the manufacture of buildings, roads, pipelines, motor vehicles, industrial machinery, etc. are not included. The energy and emissions associated with

production of capital equipment, facilities, and infrastructure generally become negligible when averaged over the total output of product or service provided over their useful lifetimes.

- **Space conditioning.** The fuels and power consumed to heat, cool, and light manufacturing establishments are omitted from the calculations when possible. For manufacturing plants that carry out thermal processing or otherwise consume large amounts of energy, space conditioning energy is quite low compared to process energy. The data collection forms developed for this project specifically requested that the data provider either exclude energy use for space conditioning or indicate if the reported energy requirements included space conditioning. Energy use for space conditioning, lighting, and other overhead activities is not expected to make a significant contribution to total energy use for the resin system.
- **Support personnel requirements**. The energy and wastes associated with research and development, sales, and administrative personnel or related activities have not been included in this study. Similar to space conditioning, energy requirements and related emissions are assumed to be quite small for support personnel activities.

INVENTORY AND IMPACT ASSESSMENT RESULTS CATEGORIES

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

The LCI and LCIA results categories and methods applied in this study are displayed in Table 1. This study addresses global, regional, and local impact categories. For most of the impact categories examined, the TRACI 2.1 method, developed by the United States Environmental Protection Agency (EPA) specific to U.S. conditions and updated in 2012, is employed.[2] 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.[3] In addition, the following LCI results are included in the results reported in the analysis:

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2 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.

3 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 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
	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,	Lb kg O_3 eq and kg O_3 eq	TRACI v2.1

	Impact/Inventory Category	Description	Unit	LCIA/LCI Methodology
		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		

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

DATA SOURCES

The purpose of this study is to develop a life cycle profile for LDPE resin using the most recent data available for each process. A weighted average was calculated for the LDPE resin data (production for the year 2015-2016) collected for this analysis. The ethylene/propylene 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 LDPE resin were collected from four producers (six plants) in North America –the United States and Canada. All companies provided data for the years 2015-2016. A weighted average was calculated from the data collected and used to develop the LCA model. The captured LDPE resin production amount is approximately 43 percent[4] of the LDPE resin production in the U.S. in 2015. Only small amounts of wax and PE scrap are coproducts of LDPE resin production, and a mass basis was used to allocate the credit for the coproducts. For coproducts sold for fuel use in other processes or steam in LDPE, these were treated as an avoided fuel product and were given credits based on the fuel they would replace.

LCI data for the production of olefins, including ethylene and propylene were collected from three producers (ten plants) in North America – all in the United States. All companies provided data for the year 2015. A weighted average was calculated from the data collected

[4] Franklin Associates calculations using resin production amounts from ACC Resin Review, 2016, p. 17.

and used to develop the LCA model. Propylene 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, and nitrogen) used to produce LDPE resin are from secondary sources. The LDPE process description 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**.

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 LDPE 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, four 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[5]. 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 nitrogen input for LDPE 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: LDPE resin manufactured in North America is produced using either autoclave or tubular high-pressure reactors. LDPE resin producers from the United States and Canada provided data from their facilities using technology ranging from old to average.

[5] 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].

This is likely due to the technology itself being older. The autoclave reactor is the older of the two types of reactor used to produce LDPE resin. Approximately half of the total LDPE resin produced by the data providers come from each type of reactor. According to 2016 LDPE resin capacity statistics in Plastics Insight[6], 80 percent of the LDPE capacity in the US and Canada is accounted to tubular reactors. It should be noted that capacity is NOT production and so this percentage may be overstated. Also from Plastics Insight, the tubular lines are more cost efficient with lesser power consumption. From this point, it can be inferred that the average dataset for LDPE resin within this report may record higher results than if 100 percent of all LDPE resin producers had provided data.

Primary data were collected from olefin 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 olefin production in North America.

LCI data from the sources of input materials specific to each company providing data was not available for this analysis. Average U.S. statistics were used were used for refined 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 LDPE 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 LDPE resin production amount (43 percent) is less than half of the total LDPE resin production in North America, data from this analysis was used to develop the most representative average for LDPE 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

[6] Statistic calculated from graphics from https://www.plasticsinsight.com/resin-intelligence/resin-prices/ldpe/

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 LDPE resin and steam cracking of the olefins. 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 offgas and, in many cases, supplied the heating value of this gas. Using this information, Franklin Associates calculated the amount of raw material combusted within the steam cracker to produce this utilized energy source.

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

Coproduct Allocation

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

multiple useful products. The practice of allocating inputs and outputs among multiple products from a process is often referred to as coproduct allocation.

Co-product 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 LDPE 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[7]. 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 LDPE 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 LDPE resin production include waxes and polyethylene scrap.

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).

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

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

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

Energy Coproducts Exported from System Boundaries

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

Electricity Grid Fuel Profile

Electricity production and distribution systems in North America are interlinked. Users of electricity, in general, cannot specify the fuels used to produce their share of the electric power grid. Data for this analysis was collected from plants in the United States. The U.S. average fuel consumption by electrical utilities was used for the electricity within this analysis. This electricity data set uses the Emissions & Generation Resource Integrated Database (eGRID) 2016 database[8].

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.

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

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

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

1. **Fuels consumed and emissions generated by the boiler:** The majority of data providers for this study reported natural gas as the fuel used for cogeneration. According to 2016 industry statistics, natural gas accounted for 75 percent of industrial cogeneration, while coal and biomass accounted for the largest portion of the remaining fuels used[9].

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.[10] 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.

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

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

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.

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 LDPE:

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 unit processes, for LDPE:

- LDPE resin production.

Tables and figures are provided for LDPE 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-LDPE and LDPE system are interchangeable). The phrase "gate-to-gate" is defined as including only the onsite process and no upstream or downstream 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 LDPE resin.

The average total energy required to produce ethylene is 34.5 million Btu per 1,000 pounds of LDPE resin or 80.3 GJ per 1,000 kilograms of LDPE resin. Table 2 shows total energy demand for the life cycle of LDPE resin production. The LDPE resin production energy has been split out from the energy required for incoming materials, including olefins production, natural gas production and processing, and petroleum extraction and refining. Only 13.6 percent of the total energy is required to produce the LDPE resin itself. The remaining energy is used to create the incoming materials from cradle-to-olefins. Approximately 11 percent of the total energy for LDPE resin production is required to create electricity for the plant itself.

Table 2. Total Energy Demand for LDPE Resin

	Basis: 1,000 pounds		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	MM Btu	***MM Btu***	***MM Btu***
Cradle-to-Olefins	29.8	29.8	0.033
Virgin LDPE Resin Production	4.70	4.52	0.17
Total	**34.5**	**34.3**	**0.20**
	Basis: 1,000 kilograms		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	GJ	***GJ***	***GJ***
Cradle-to-Olefins	69.4	69.3	0.076
Virgin LDPE Resin Production	10.9	10.5	0.39
Total	**80.3**	**79.8**	**0.47**
	Percentage		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	%	***%***	***%***
Cradle-to-Olefins	86.4%	86.3%	0.1%
Virgin LDPE Resin Production	13.6%	13.1%	0.5%
Total	**100%**	**99.4%**	**0.6%**

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 LDPE resin, 99.4 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 (0.39 GJ/1000 kg) used at the LDPE resin plant, 98 percent comes from hydropower and other renewable sources (geothermal, solar, etc.) from electricity production used in the LDPE resin production.

The energy representing natural gas and petroleum used as raw material inputs for the production of ethylene used to produce LDPE resin are included in the cradle-to-olefins amounts in Table 2. The energy inherent in these raw materials are called 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 LDPE resin. Approximately 63 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 LDPE resin. Ninety percent of the feedstock sources for ethylene come from natural gas, while 10 percent of the feedstock sources come from oil.

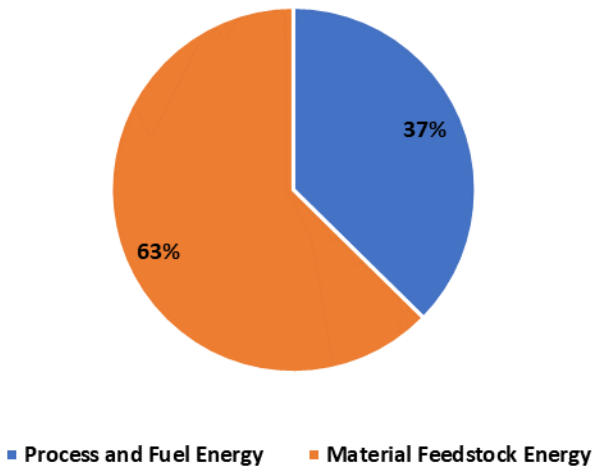

Figure 3. Process/Fuel and Material Feedstock Percentages for LDPE Resin

Energy Demand by Fuel Type

The total energy demand by fuel type for LDPE is shown in Table 3 and the percentage mix is shown in Figure 4. Natural gas and petroleum together make up almost 94 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 LDPE 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 LDPE resin in the following tables and figures represents the energy required for transportation of raw materials to LDPE manufacturers, the energy required to produce the LDPE resin, and the production of the fuels needed to manufacture the LDPE.

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

Of the results for LDPE resin production shown in Table 3 and Figure 4, over 85 percent of the energy used (69.8 GJ/80.3 GJ) is from natural gas. At the LDPE resin plant, more than half of the energy used (6.42 GJ/10.9 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 for LDPE resin is required to create electricity off-site. Petroleum comprises approximately 1 percent (0.13 GJ/10.9 GJ) of the fuel used for LDPE resin production; most of this petroleum is combusted to create electricity. The coal use shown is combusted for electricity use. The 2016 U.S. electricity grid is used for this study. In this grid, approximately 30 percent of the electricity production in the US uses coal as a fuel source, 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 LDPE 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-Olefins	29.8	27.3	2.33	0.12	0.082	0.0087	0.024
Virgin LDPE Resin Production	4.70	2.76	0.055	1.02	0.69	0.073	0.10
Total	**34.5**	**30.0**	**2.39**	**1.14**	**0.77**	**0.081**	**0.13**
	Basis: 1,000 kilograms						
	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
	GJ	*GJ*	*GJ*	*GJ*	*GJ*	*GJ*	*GJ*
Cradle-to-Olefins	69.4	63.4	5.43	0.29	0.19	0.020	0.057
Virgin LDPE Resin Production	10.9	6.42	0.13	2.37	1.59	0.17	0.24
Total	**80.3**	**69.8**	**5.56**	**2.65**	**1.79**	**0.19**	**0.29**
	Percentage of Total						
	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
	%	*%*	*%*	*%*	*%*	*%*	*%*
Cradle-to-Olefins	86.4%	79.0%	6.8%	0.4%	0.2%	0.03%	0.07%
Virgin LDPE Resin Production	13.6%	8.0%	0.2%	2.9%	2.0%	0.2%	0.30%
Total	**100%**	**87.0%**	**6.9%**	**3.3%**	**2.2%**	**0.2%**	**0.4%**

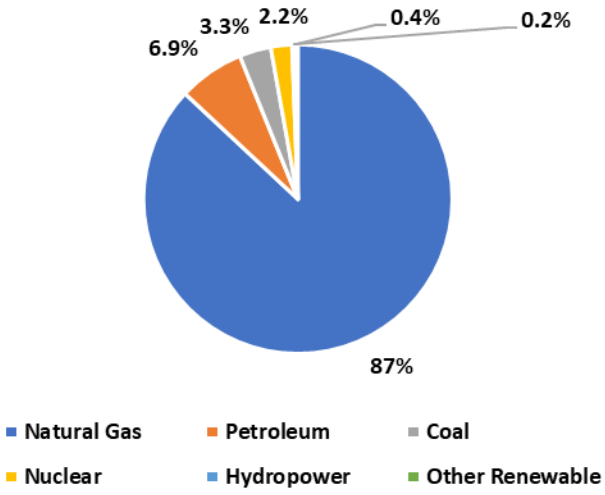

Figure 4. Percentage of Energy Separated by Fuel Type for LDPE Resin

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 olefins (e.g., sludges and residues from chemical reactions and material processing steps)
- **Fuel-related wastes** from the production and combustion of fuels used for process energy and transportation energy (e.g., refinery wastes, coal combustion ash)

No postconsumer wastes of the LDPE 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 LDPE 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 the incoming materials (cradle-to-olefins) and the LDPE plant. As shown in Figure 5, more than 50 percent of the total solid waste is created during the LDPE resin unit process. This comes from fuel combusted or as a process solid waste during the LDPE production. The greatest amount of solid waste from the LDPE process comes from coal production and combustion used to create electricity for the LDPE resin plant. Only 4 percent of the total solid wastes are process wastes from the LDPE resin plant.
The remaining half of the solid waste comes from the production of incoming materials used to produce LDPE resin. Approximately 90 percent of the raw materials used to create olefins 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 8 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 2.5 percent of the total solid wastes were considered hazardous wastes. Of that percentage, a little less than 60 percent come from the olefins plant, with the remaining attributed to the LDPE unit process.

Table 4 also provides a breakout of the total solid wastes by the disposal fate. Of the hazardous waste, only 1 percent is landfilled; while about 60% is incinerated without energy capture and 40 percent incinerated with energy capture. Focusing specifically on the non-hazardous solid waste produced, 92 percent of the solid waste is landfilled, while 8 percent is incinerated, and a minute amount (0.001%) sent to waste-to-energy.

Table 4. Total Solid Wastes for LDPE 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-Olefins	48.6	0	1.40	0.0031	1.41	6.1E-04	6.02	41.2	47.2
Virgin LDPE Resin Production	46.7	0.95	0.0082	0.021	0.98	0	1.40	44.4	45.8
Total	**95.3**	**0.95**	**1.41**	**0.024**	**2.39**	**6.1E-04**	**7.42**	**85.5**	**92.9**
	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-Olefins	48.6	0	1.40	0.0031	1.41	6.1E-04	6.02	41.2	47.2
Virgin LDPE Resin Production	46.7	0.95	0.0082	0.021	0.98	0	1.40	44.4	45.8
Total	**95.3**	**0.95**	**1.41**	**0.024**	**2.39**	**6.1E-04**	**7.42**	**85.5**	**92.9**
	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-Olefins	51.0%	0%	1.5%	0.003%	1.5%	0.001%	6.3%	43.2%	49.5%
Virgin LDPE Resin Production	49.0%	1.0%	0%	0.02%	1.0%	0%	1.5%	46.5%	48.0%
Total	**100%**	**1.0%**	**1.5%**	**0.03%**	**2.5%**	**0.001%**	**7.8%**	**89.7%**	**97.5%**

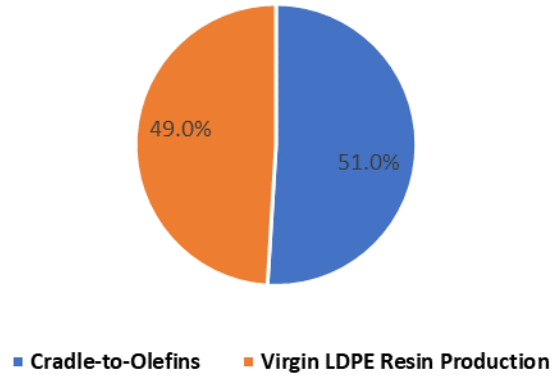

Figure 5. Percentage of Total Solid Wastes for LDPE Resin System

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 LDPE resin production are shown in Table 5 and Figure 6. The consumption of water within the LDPE resin is evenly split between the LDPE resin production and all other processes required to produce the LDPE. When looking at the individual unit processes, about 30 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 LDPE resin average data also includes some plants that release water to a different watershed. The LDPE resin plant water consumption amount comprises 25 percent of the total. 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 approximately 25 percent of the total water consumption. Over 12 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 fuels used.

Table 5. Water Consumption for LDPE Resin

	Total Water Consumption		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	Gallons	*Liters*	*%*
Cradle-to-Olefins	702	5,855	50.7%
Virgin LDPE Resin Production	683	5,698	49.3%
Total	**1,385**	**11,553**	**100%**

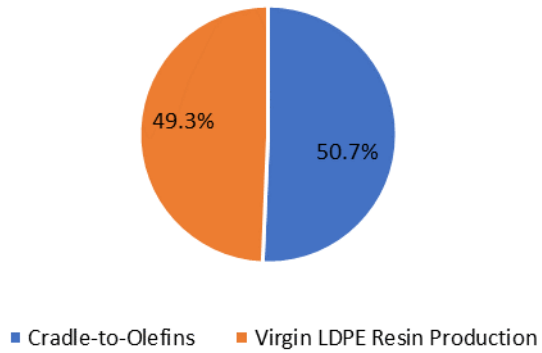

Figure 6. Water Consumption for LDPE Resin

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 LDPE 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[11] 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 LDPE resin system. Of the total, 64 percent of the GWP are attributed to emissions from the natural gas and petroleum input materials and olefins production, with the remaining GWP associated with the production of LDPE resin. The largest amount of the GWP is created by the production of ethylene, which accounts for 36 percent of the total GWP, which comes directly from the release of greenhouse gases at the olefins plant. A little more than 1 percent of the total GWP is created by the LDPE resin plants. Over 30 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 almost 20 percent of the total GWP.

[11] 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 LDPE Resin

	Global Warming Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CO2 eq	*kg CO2 eq*	*%*
Cradle-to-Olefins	1,243	1,243	64%
Virgin LDPE Resin Production	684	684	36%
Total	**1,927**	**1,927**	**100%**

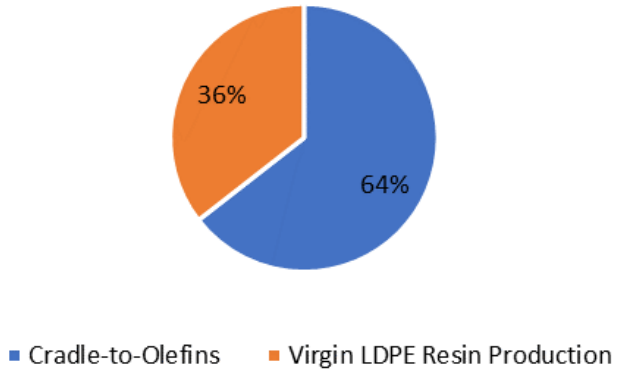

Figure 7. Global Warming Potential for LDPE Resin

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.[12,13]

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

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12 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.

13 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 LDPE resin system. Results are shown graphically in Figure 8. The AP category is split with 40 percent of the AP coming from LDPE resin production and about 60 percent coming from the raw and intermediate material unit processes. As stated previously, much of the AP amount (34 percent) comes from the combustion of coal during the creation of electricity, which is used in all unit processes. Over half of the AP (54 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 3 percent of the AP results come from emissions released at the olefins plants, and less than 1 percent from the LDPE resin plants.

Table 7. Acidification Potential for LDPE Resin

	Acidification Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb SO2 eq	*kg SO2 eq*	*%*
Cradle-to-Olefins	3.89	3.89	59.4%
Virgin LDPE Resin Production	2.65	2.65	40.6%
Total	**6.54**	**6.54**	**100%**

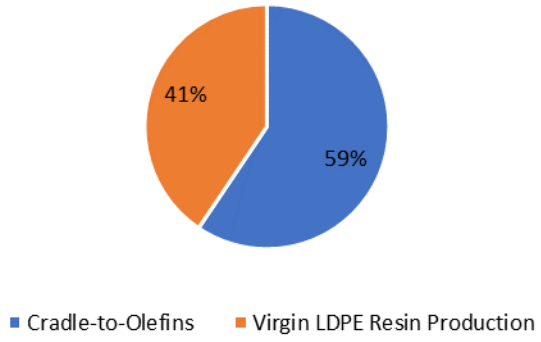


Figure 8. Acidification Potential for LDPE Resin

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.[14] The TRACI characterization factors for

[14] 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.[15] 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 LDPE resin are shown in Table 8 and illustrated in Figure 9. The largest portion, over 75 percent, of the EP results come from the raw and intermediate materials used to create LDPE resin. Within this amount, the extraction of natural gas for materials and fuels releases 63 percent of the emissions related to the EP impact. The olefins plant process emissions comprise 11 percent of the EP impact results. The LDPE resin production generates 24 percent of the EP impact, with three-quarters of that percentage representing the combustion of coal and natural gas for electricity. Only 3 percent of the total EP impact comes from process emissions released at the LDPE plant.

Table 8. Eutrophication Potential for LDPE Resin

	Eutrophication Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb N eq	*kg N eq*	*%*
Cradle-to-Olefins	0.23	0.23	76.4%
Virgin LDPE Resin Production	0.071	0.071	23.6%
Total	**0.30**	**0.30**	**100%**

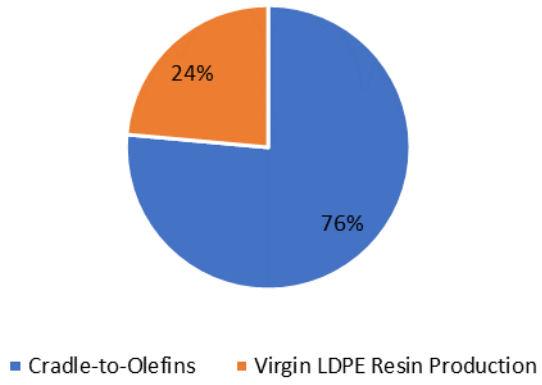


Figure 9. Eutrophication Potential for LDPE Resin

[15] 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 LDPE 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 LDPE resin system, which are also shown graphically in Figure 10. Ozone depletion results for the LDPE resin system are dominated by the crude oil extraction and refining system, contributing 99 percent of the total ozone depletion impacts. The amount of the ODP shown as LDPE resin production is from the production of petroleum-based fuels used within the plant. No emissions impacting ODP are released at the ethylene or LDPE plants.

Table 9. Ozone Depletion Potential for LDPE 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-Olefins	1.2E-06	1.2E-06	97.3%
Virgin LDPE Resin Production	3.4E-08	3.4E-08	2.7%
Total	**1.3E-06**	**1.3E-06**	**100%**

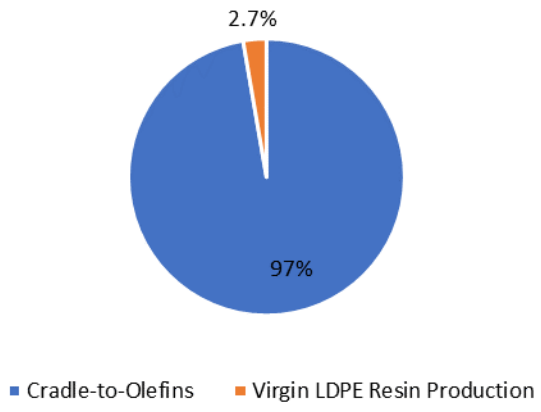


Figure 10. Ozone Depletion Potential for LDPE Resin

PHOTOCHEMICAL SMOG FORMATION

The photochemical smog formation (POCP) impact category characterizes the potential of airborne emissions to cause photochemical smog. The creation of photochemical smog occurs when sunlight reacts with NO_x and volatile organic compounds (VOCs), resulting in tropospheric (ground-level) ozone and particulate matter. Endpoints of such smog creation can include increased human mortality, asthma, and deleterious effects on plant growth.[16] 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 70 percent of the total results.

Smog formation potential results for LDPE resin are displayed in Table 10 and illustrated in Figure 11. Approximately 76% 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 (70 percent) of the total POCP impact results within the cradle-to-olefins 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.

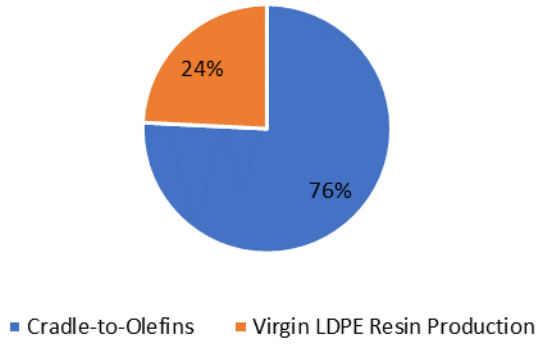
The remaining 24 percent of the POCP impact results is released from the LDPE resin production process. Almost 85 percent of the POCP from the LDPE resin plant comes from the use of electricity in the plant, which includes the combustion of natural gas and coal at power plants and cogeneration plants. Only 1 percent of the total emissions resulting in the POCP impact results are released at the LDPE resin plant as process emissions.

Table 10. Photochemical Smog Formation Potential for LDPE Resin

	Photochemical Smog Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb O3 eq	*kg O3 eq*	*%*
Cradle-to-Olefins	112	112	75.8%
Virgin LDPE Resin Production	35.8	35.8	24.2%
Total	**148**	**148**	**100%**

[16] 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 LDPE Resin



COMPARISON OF 2019 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 LDPE system[17] 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 2019 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 global warming potential. The solid waste and renewable energy amounts are higher than the previous analysis from 2011. An increase in the 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 mostly due to the use of additional or different companies and manufacturing plants when replacing the ethylene and LDPE primary data. 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 LDPE resin and ethylene in 2016-2018. For ethylene and LDPE, some of the same plants were included; however, many of the plants in the averages were not included

[17] 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.

in the original data collection in 2004-2006. More plants participated in the data collection for this update for the ethylene resin. Also, the number of companies participating in this update for the LDPE resin increased, although the plant number decreased by one.
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Table 11. Comparison of 2011 and 2019 LCI and LCIA Results for Virgin LDPE Resin

	1000 pounds of Virgin Low-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*
LDPE 2019	34.5	34.3	0.20	92.9	1,927
LDPE 2011	35.9	35.8	0.11	81.2	2,201
	1000 kilograms of Virgin Low-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*
LDPE 2019	80.3	79.8	0.47	92.9	1,927
LDPE 2011	83.6	83.4	0.26	81.2	2,201
Percent Change	-4%	-4%	81%	14%	-12%

*Total Solid Waste excludes hazardous solid waste for 2019 as this category was not included as Solid Waste in 2011.

ENERGY COMPARISON

Overall, the total energy for LDPE resin has decreased 3.3 GJ on a 1,000 kg basis (1.4 MMBtu/1,000 lb). This is a 4 percent decrease in total energy as compared to the original results. When comparing the LDPE resin unit process average energy data, there is not an across the board decrease between data from plants that were collected for both studies. In some of these plants, the electricity amounts had increased by small amounts while the natural gas amounts had decreased, while the opposite was true in other plants. For some plants these could be explained by efficiency improvements or small decreases in required input materials. Plus, 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.

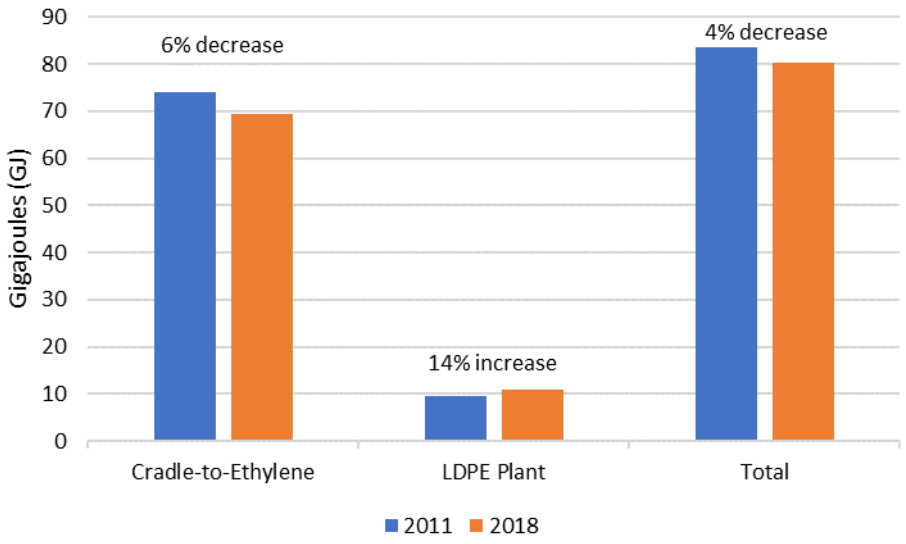

Figure 12. Decrease in Energy by Stage per 1,000 kg (GJ)

The energy of material resource, which pertains to the amount of inherent energy from the raw materials, decreased by 0.8 GJ per 1,000 kg of LDPE 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. The energy specific to the LDPE plant increased by 14 percent of its previous total. This can be accounted for due to the differences in plants providing data. Although 5 of the 6 plants providing data had also provided data in the 2011 report, the production amounts used to weight the averages as well as the energy used at the plants accounted for the increase in total energy, which was 0.8 GJ/1000 kg of LDPE resin. This increase in energy was offset by the decrease in energy (3.3 GJ/1000 kg of LDPE resin) shown in the cradle-to-olefins 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 an 81 percent increase from the original results. Although this seems quite large, 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 LDPE resin total solid waste amount, the current LDPE resin study creates almost 12 kg/1000 kg LDPE resin more solid waste, which is a 17 percent increase. Some of this increase is due to the differences in olefin and LDPE plant data collected between the 2011 and 2019 reports, as well as their weighting using production amounts. Figure 13 provides a visual of the total solid waste amount split out by the LDPE unit process and cradle-to-olefins. A decrease occurs in the raw materials and olefins production, while a larger increase is shown for the LDPE plants. The LDPE plant process solid waste did increase but is a very small part of the total process and fuel wastes for that unit process. This large increase in the LDPE solid waste process comes from the change from using more cogeneration created electricity (using natural gas mainly as a fuel) in the 2011 study to using grid generated electricity (using more coal as a fuel) in the current study. 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.

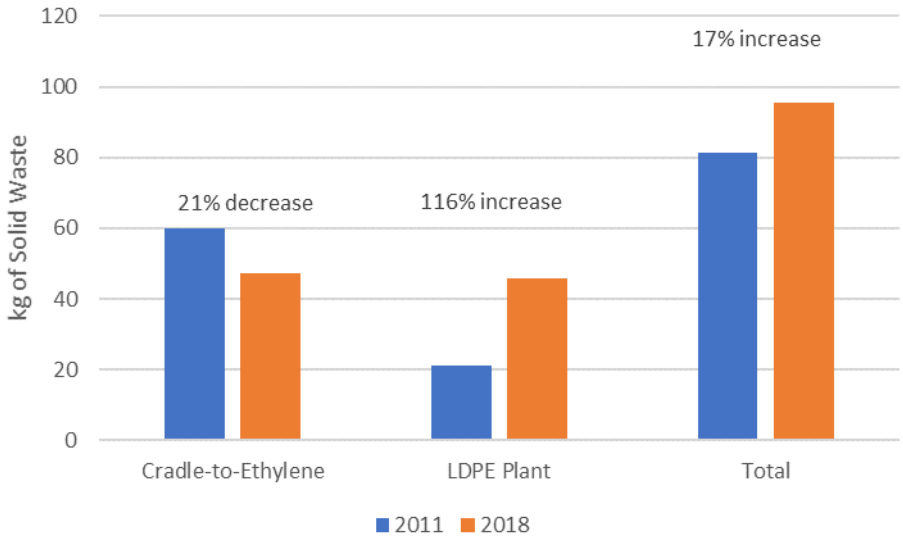

Figure 13. Decrease in Solid Waste Weight by Unit Process (kg Per 1,000 kg)

GLOBAL WARMING POTENTIAL COMPARISON

The global warming potential decreased by 274 kg CO_2 equivalents/1000 kg LDPE resin, or 12 percent compared to the 2011 LDPE resin GWP result. Figure 14 displays a column chart with the LDPE resin and cradle-to-olefins results that makeup the decrease when comparing the 2011 and 2018 GWP results. For the most part, this overall decrease follows the trend shown in total energy, since much of the greenhouse gases are created from fuel production.

The GWP for the LDPE resin plant increases due to a decrease in using cogeneration electricity to increased grid electricity in the average, due to the difference in plants providing data. Coal production and combustion releases higher amounts of greenhouse gases compared to natural gas production and combustion. The decrease in GWP for Olefins comes from decreases in energy use for the raw materials and for the olefins plant.

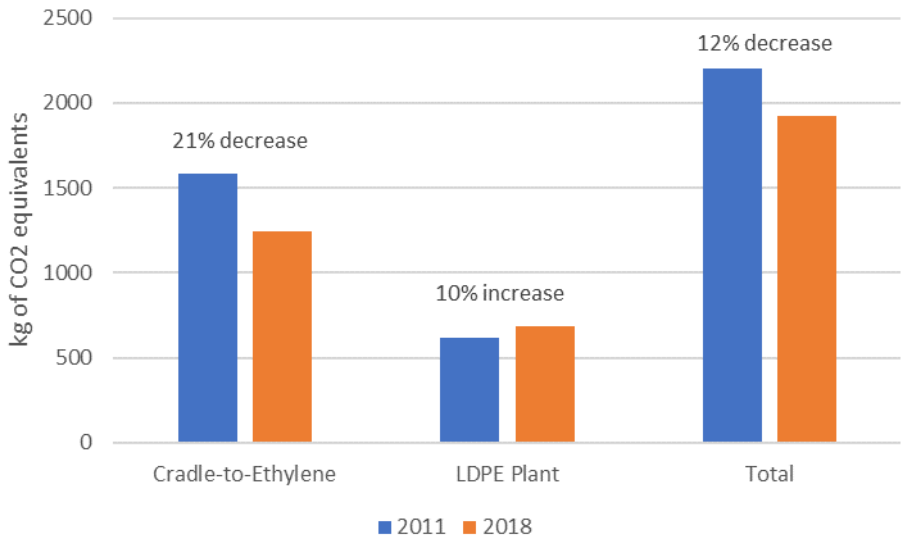

Figure 14. Decrease in Global Warming Potential by Unit Process (kg of CO2 eq. per 1,000 kg)

APPENDIX: LOW-DENSITY POLYETHYLENE (LDPE) MANUFACTURE

This appendix discusses the manufacture of LDPE, which is used for many plastics products, including plastic wrap, shipping envelopes, 6-pack rings, and general-purpose containers. The captured LDPE production amount is approximately 43 percent of the LDPE production in the U.S. in 2015 (ACC, 2016). The flow diagram of processes included for LDPE 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:

- Low-density Polyethylene (LDPE) Production

LCI data for olefins and LDPE 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. 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***.

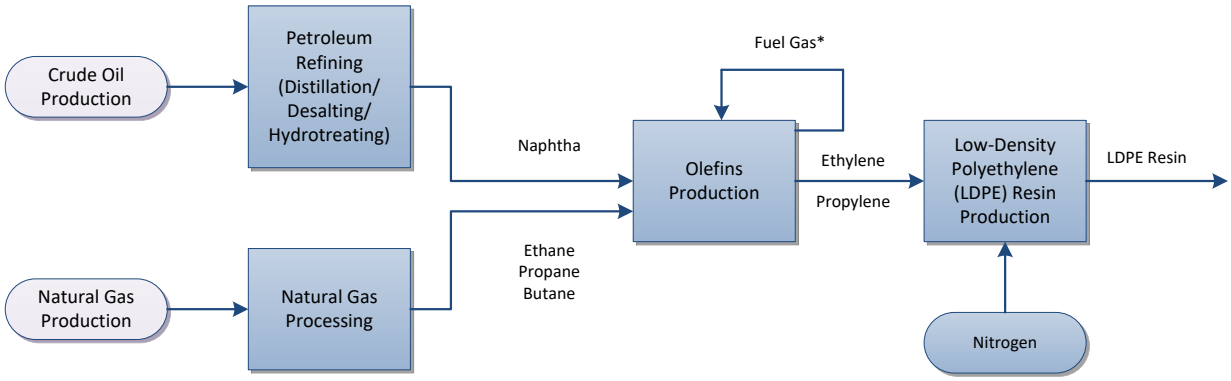

Figure 15. Flow diagram for the Production of Low-Density Polyethylene (LDPE).
*Fuel gas used for energy is created from off-gas produced in the process.

LOW-DENSITY POLYETHYLENE (LDPE) PRODUCTION

The main raw materials for LDPE production are ethylene and propylene, which typically come from a steam cracker. These 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, low-density polyethylene (LDPE) is produced by the polymerization of mainly ethylene in high pressure reactors (above 3,000 psi). This is the

standard technology for LDPE production globally. The two reactor types used are autoclaves and tubular reactors. Generally, tubular reactors operate at a higher average ethylene conversion with lesser power consumption than autoclave reactors. The polymerization mechanism is either free-radical, using peroxide initiators, or ionic polymerization, using Ziegler catalyst.

Reactor effluent consists of unreacted ethylene and polymer. The pressure of the effluent mixture is reduced and the ethylene is purified and recycled back to the reactor.

An individual weighted average for four leading LDPE resin producers (6 LDPE units) was calculated using LDPE resin production amounts from each plant. Companies were requested to provide data for the year 2015, but were allowed to use 2016 to alleviate issues, such as numerous shutdowns or other plant issues, that would provide anomalous data for the year. Two companies provided data for the year 2015, and two companies provided data for the year 2016. A weighted average was calculated from the data collected and used to develop the LCA model. Scrap, waxes, and steam are produced as coproducts during this process. A mass basis was used to partition the credit for scrap. For steam used in other processes, this was treated as an avoided fuel product and were given credits based on the fuel required to create the steam that it would replace.

The captured LDPE production amount is approximately 43 percent of the LDPE production in the U.S. in 2015 (ACC, 2016). While data was collected from a relatively small sample of plants, the LDPE resin producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American LDPE resin production. LDPE resin producers from the United States and Canada provided data from their facilities using technology ranging from old to average. This is likely due to the technology itself being older. The autoclave reactor is the older of the two types of reactor used to produce LDPE resin. Approximately half of the total LDPE resin produced by the data providers come from each type of reactor.

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 12 shows the averaged energy and emissions data for the production of 1,000 pounds and 1,000 kilograms of LDPE. 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 Low-Density Polyethylene (LDPE)

	1,000 lb		1,000 kg		
Material Inputs (1)					
Ethylene	996	lb	996	kg	
Propylene	6.96	lb	6.96	kg	
Nitrogen	10.1	lb	10.1	kg	
	1,000 lb		**1,000 kg**		
Energy					
Process Energy					
Electricity from grid	308	kWh	679	kWh	
Electricity from cogen	122	kWh	268	kWh	
Natural gas	932	ft^3	58.2	m^3	
Avoided Energy					
Recovered energy from exported steam	97.5	ft^3	6.08	m^3	
Purged Ethylene	121	ft^3	7.55	m^3	
Transportation Energy					
Truck	0.065	ton·mi	0.21	tonne·km	
Rail	0.0011	ton·mi	0.0034	tonne·km	
Pipeline -refinery products	8.69	ton·mi	28.0	tonne·km	
Environmental Emissions					
Atmospheric Emissions					
Particulates, unspecified	0.025	lb	0.025	kg	
Particulates, < 2.5 um	0.0088	lb	0.0088	kg	
Particulates, > 2.5 um, and < 10um	0.035	lb	0.035	kg	
Nitrogen oxides	0.076	lb	0.076	kg	
Sulfur oxides	0.0031	lb	0.0031	kg	
Carbon dioxide, fossil	26.1	lb	26.1	kg	
Methane	0.0074	lb	0.0074	kg	
Nitrous oxide	0.0025	lb	0.0025	kg	
HFC (unspec.)	0.0010	lb	0.0010	kg	*
Carbon monoxide	0.081	lb	0.081	kg	
Aldehydes, unspecified	1.0E-04	lb	1.0E-04	kg	*
VOC, volatile organic compounds	1.0E-04	lb	1.0E-04	kg	*
Propane	1.0E-04	lb	1.0E-04	kg	*
Methanol	0.0010	lb	0.0010	kg	*
1-Hexene	0.0010	lb	0.0010	kg	*
Isopentane	0.0010	lb	0.0010	kg	*
Naphthalene	1.0E-09	lb	1.0E-09	kg	*
Ethane	0.0010	lb	0.0010	kg	*
Isobutane	0.010	lb	0.010	kg	*
Hydrocarbons, unspecified	0.32	lb	0.32	kg	(1)
Isopropanol	0.010	lb	0.010	kg	*
Ethylene	0.63	lb	0.63	kg	
Propylene	0.013	lb	0.013	kg	

Table 12. LCI Data for the Production of Low-Density Polyethylene (LDPE) (Continued)

	1,000 lb		1,000 kg		
Waterborne Releases					
Dissolved solids	1.0E-05	lb	1.0E-05	kg	*
BOD5, Biological Oxygen Demand	0.010	lb	0.010	kg	*
COD, Chemical Oxygen Demand	0.10	lb	0.10	kg	*
Phenolics	1.0E-07	lb	1.0E-07	kg	*
Oils, unspecified	1.0E-05	lb	1.0E-05	kg	*
Suspended solids, unspecified	0.027	lb	0.027	kg	
Aluminium	1.0E-04	lb	1.0E-04	kg	*
Nickel	1.0E-09	lb	1.0E-09	kg	*
Zinc	1.0E-05	lb	1.0E-05	kg	*
DOC, Dissolved Organic Carbon	0.0010	lb	0.0010	kg	*
Phosphorus	1.0E-04	lb	1.0E-04	kg	*
Methane, trichlorofluoro-, CFC-11	1.0E-04	lb	1.0E-04	kg	*
2-Propanol	1.0E-04	lb	1.0E-04	kg	*
Solid Wastes					
Solid waste, process to landfill	1.16	lb	1.16	kg	
Solid Waste Sold for Recycling or Reuse	4.76	lb	4.76	kg	
Solid waste, process to incineration	1.44	lb	1.44	kg	
Hazardous waste to landfill	0.021	lb	0.021	kg	
Hazardous waste to incineration	0.0082	lb	0.0082	kg	
Hazardous waste to WTE	0.95	lb	0.95	kg	
Water Consumption	349	gal	2,913	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) Includes hydrocarbons and non-methane hydrocarbons

Source: Primary Data, 2018

REFERENCES

Primary Data (2018). Primary data from 2015 collected from 4 LDPE producers by Franklin Associates. 2017-2018.

American Chemistry Council (2016), *Resin Review 2016, The Annual Statistical Report of the North American Plastics Industry*. April, 2016.