CRADLE-TO-GATE LIFE CYCLE ANALYSIS OF POLYPROPYLENE (PP) RESIN

Final Report

Submitted to:

American Chemistry Council (ACC) Plastics Division

Submitted by:

Franklin Associates, A Division of ERG

February, 2021

PREFACE

This life cycle assessment of polypropylene (PP) 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 PP 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 and appendix preparation. Mariya Absar aided with modeling and report writing. 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: ExxonMobil Corporation, Lyondellbasell Industries, and INEOS, who graciously provided primary Life Cycle Inventory data for PP resin 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.

February, 2021

TABLE OF CONTENTS

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
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)
PP	POLYPROPYLENE
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 POLYPROPYLENE (PP) RESIN

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 polypropylene (PP) resin, which is used in a variety of end use applications, including injection molded packaging, automotive/appliance parts, fibers used in upholstery fabrics and carpeting, and films. 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.

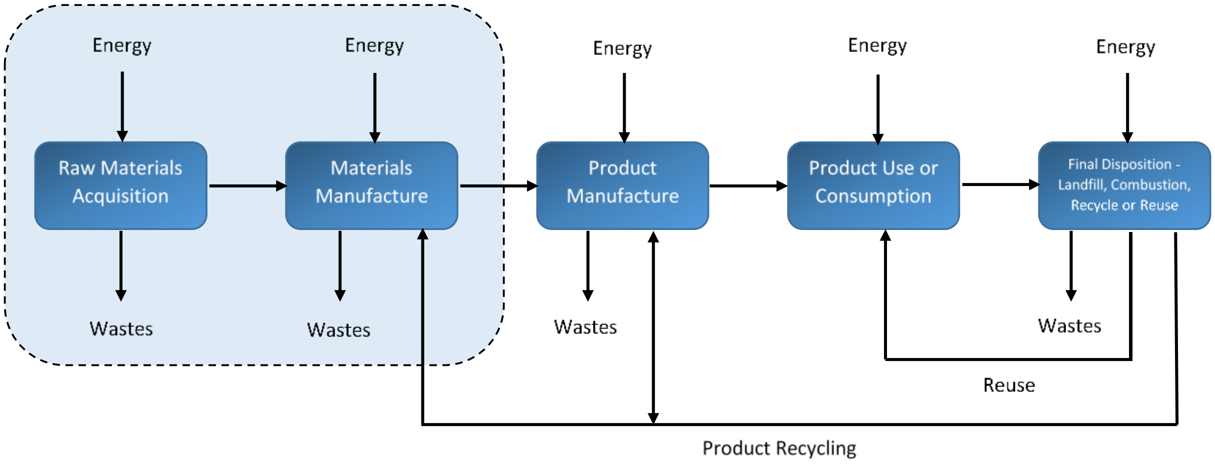

Figure 1. General materials flow for “cradle-to-grave” analysis of a product system. The dashed box indicates the boundaries of this analysis.

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 PP resin. It is considered a cradle-to-gate boundary system because this analysis ends with the PP resin production. The system boundaries stop at the PP 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 applications, such as injection molded products, fibers and film. 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 PP 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.

---

[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. Submitted to the Plastics Division of the American Chemistry Council. 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 PP 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 PP resin and
- To provide information about the environmental burdens associated with the production of PP resin. The LCA results for PP production can be used as a benchmark for evaluating future updated PP 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 acting on behalf of its Plastics Division and may be used by the trade association or members of ACC's Plastics Division or the general public at ACC's discretion.

FUNCTIONAL UNIT

The function of PP resin is its forming into various products, for example, carpet or food containers. As the study boundary concludes at the PP 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 PP 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 PP 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
- PP resin manufacture, including incoming transportation for each material.

Because upstream olefin manufacture impacts the results for the production of PP, some discussion of propylene data and meta-data is included throughout this report. However, the LCI data for the olefins system is provided in the appendix of a separate report, *Cradle-to-Gate Life Cycle Analysis of Olefins*[3]. This report presents LCI results, as well as LCIA results, for PP resin manufacture. Figure 2 presents the flow diagram for the production of PP resin. A unit process description and tables for each box shown in the flow diagram can be found in the attached appendix or in the olefins report previously released.

---

[3] Cradle-to-Gate Life Cycle Analysis of Olefins. Franklin Associates. Submitted to the Plastics Division of the American Chemistry Council. April, 2020.

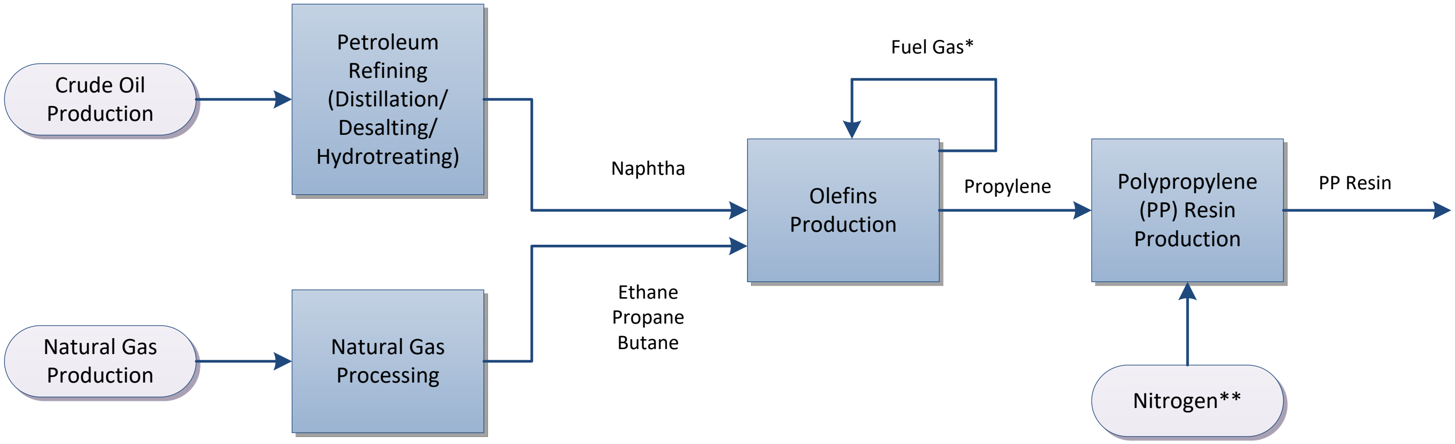

Figure 2. Flow diagram for the Production of Polypropylene (PP) Resin.

* Fuel gas used for energy is created from off-gas produced in the process.
** Nitrogen data is from ecoinvent and is adapted to U.S. conditions. Nitrogen is an ancillary material input.

Technological Scope

The two main technologies used to manufacture polypropylene are the bulk slurry and the gas-phase processes. Spheripol, a type of bulk slurry technology, and Unipol, a type of gas-phase technology are used by the data providers. According to an article on Plastics Insight[4], of the world production of PP resin, 39 percent of PP resin manufacturers used Spheripol, while 16 percent of PP manufacturers used the Unipol technology. A number of other patented technologies are used at a lower percentage. No information was found about the representativeness of those percentages within North America.

In the bulk slurry technology, polymerization is carried out in liquid propylene in tubular loop reactors[5].Catalysts and liquid propylene are continually fed into a prepolymerization reactor, then sent to a series of bulk loop reactors to form PP granules. Small amounts of hydrogen are added to control PP properties. Any excess propylene monomer is removed from the polymer granules using vaporization operations[6]. The monomer stream is purified and recycled to the reactor. The remaining PP granules are then sent to extrusion for pelletization.

The gas-phase technology uses a fluidized bed reactor framework[7] (Chem Eng, May, 2013). The propylene feedstock is degassed to rid it of any oxygen or other unwanted materials. The feedstock is then cooled and sent to a dryer before it is sent to the gas-stage polymerization reactor. Small amounts of hydrogen are added to control the properties of the PP. The polymer is taken out intermittently from the reactor using separators. The excess monomer propylene is recycled back to the reactor. The polypropylene is removed from the separators as a powder. These PP granules are sent to extrusion for pelletization.

Temporal and Geographic Scope

To assess the quality of the data collected for PP, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for PP include direct measurements, information provided by purchasing and utility records, and estimates. The technology represented by the PP data represents a combination of the liquid monomer and gas phase processes. All data submitted for PP represent the years 2015-2016 and production in U.S.

For the PP resin primary data, companies were requested to provide data for the year 2015, the most recent full year of PP 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 one company provided data for the year

---

[4] Plastics Insight. All About Polypropylene (PP): Production, Price, Market & its Properties. Available at https://www.plasticsinsight.com/resin-intelligence/resin-prices/polypropylene/

[5] Chem Eng (Sept 2013). Propylene Bulk Phase Process. Chemical Engineering. September 1, 2013

[6] Lyondellbasell. Lyondellbasell brochure from www.lyondellbasell.com/technology. Accessed 2020.

[7] Chem Eng (May 2013) Propylene Production via Gas-Phase Process. Chemical Engineering. May 1, 2013

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 PP resin production at their company.

The geographic scope of the analysis is the manufacture of PP resin in North America. All PP resin data collected were from plants in the United States and some input materials were modeled using North American databases such as the U.S. LCI database and Franklin Associates' private database, as well as ecoinvent. All 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 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.[8] 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.[9] In addition, the following LCI results are included in the results reported in the analysis:

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

---

[8] 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.

[9] 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, 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

DATA SOURCES

The purpose of this study is to develop a life cycle profile for PP resin using the most recent data available for each process. A weighted average was calculated for the PP resin data (production for the year 2015-2016) collected for this analysis. The 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 PP resin were collected from three producers (three 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 PP resin production amount is approximately 16 percent[10] of the PP resin production in the U.S. in 2015. Only small amounts of off-spec and trim product are coproducts of PP resin production, and a mass basis was used to allocate environmental burdens among the coproducts.

LCI data for the production of olefins, including 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 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.

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 PP 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, three companies each provided current, geographically representative data for all primary PP data collected for this LCA.

The incoming material and fuel datasets for PP manufacture 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[11]. 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 PP resin is the only process from secondary sources. The data

---

[10] American Chemistry Council, Resin Review 2016. Franklin Associates calculations.

[11] 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].

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: PP resin manufactured in North America is produced using either a bulk slurry process or gas process within the United States. The three companies provided data from their facilities using technology ranging from average to state-of-the-art. Approximately two-thirds of the total PP resin produced by the data providers come from the solution technology. According to 2015 PP resin capacity statistics by IHS Markit[12], 16 percent of the PP capacity globally is accounted to gas-phase technology with solution technology making up 39 percent, while other technologies are used in smaller amounts; however, it is unknown if this is representative of North America specifically.

The LCI data for the olefins system is shown in the appendix of a separate report, *Cradle-to-Gate Life Cycle Analysis of Olefins*[13]. Primary data were collected from propylene manufacturers from the year 2015. Companies providing data were given the option to collect data from the year preceding or following 2015 if either year would reflect more typical production conditions. After reviewing individual company data in comparison to the average, each manufacturer verified data from 2015 was a representative year for propylene 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 PP 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. Data from this analysis was

---

[12] Plastics Insight. All About Polypropylene (PP): Production, Price, Market & its Properties. 2016 data. https://www.plasticsinsight.com/resin-intelligence/resin-prices/polypropylene/

[13] Cradle-to-Gate Life Cycle Analysis of Olefins. Franklin Associates. Submitted to the Plastics Division of the American Chemistry Council. April, 2020.

used to develop the most representative average for PP 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.

Order of Magnitude: In some cases, emissions data were reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only as an order of magnitude. An order of magnitude of a number is the smallest power of 10 used to represent that number. For example, if the average of two data points for a particular emission is 2.5E-4, the amount would be shown as 1.0E-4 to ensure confidentiality of the data providers but allow the impact assessment tool to include a close estimate of the amount within any pertinent impact categories. When order of magnitude is used in the LCI data shown in the Appendix of this report, it is clearly noted by an asterisk next to the amount.

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 PP 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 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.

Environmental burdens are allocated among the coproducts 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 PP 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[14]. 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

---

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

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 PP 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 PP resin production include off-spec and trim 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).

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

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 [15].

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

Electricity/Heat Cogeneration

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

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

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

1. **Fuels consumed and emissions generated by the boiler:** The majority of data providers for this study reported natural gas as the fuel used for cogeneration. According to 2016 industry statistics, natural gas accounted for 75 percent of industrial cogeneration, while coal and biomass accounted for the largest portion of the remaining fuels used[16].

---

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

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

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.[17] 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.

---

[17] 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 PP:

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 PP:

- Cradle-to-incoming materials – includes the raw materials through the production of propylene inputs
- PP resin production – is the gate-to-gate unit process and includes the production of fuels & nitrogen used in the process.

Tables and figures are provided for PP 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/resin stated in the term (e.g. cradle-to-PP and PP system are interchangeable). The phrase "gate-to-gate" is defined as including only the onsite process/fuels/nitrogen.

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 PP resin.

The average total energy required to produce PP is 32.5 million Btu per 1,000 pounds of PP resin or 75.5 GJ per 1,000 kilograms of PP resin. Table 2 shows total energy demand for the life cycle of PP resin production. The PP resin production energy has been split out from the energy required for incoming materials, including the production of propylene, natural gas production and processing, and petroleum extraction and refining. Only 6 percent of the total energy is required to produce the PP resin itself. The remaining 94 percent is used to create the incoming materials and their raw materials.

Table 2. Total Energy Demand for PP Resin

	Basis: 1,000 pounds		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	MM Btu	***MM Btu***	***MM Btu***
Cradle-to-Incoming Materials	30.6	30.6	0.031
Virgin PP Resin Production	1.86	1.81	0.050
Total	**32.5**	**32.4**	**0.081**
	Basis: 1,000 kilograms		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	GJ	***GJ***	***GJ***
Cradle-to-Incoming Materials	71.2	71.1	0.073
Virgin PP Resin Production	4.33	4.21	0.12
Total	**75.5**	**75.3**	**0.19**
	Percentage		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	%	***%***	***%***
Cradle-to-Incoming Materials	94.3%	94.2%	0.1%
Virgin PP Resin Production	5.7%	5.6%	0.2%
Total	**100%**	**99.8%**	**0.2%**

Non-renewable energy demand includes the use of fossil fuels (petroleum, natural gas, and coal) for process energy, transportation energy, and as material feedstocks (e.g., oil and gas used as feedstocks for the production of the propylene), as well as use of uranium to generate the share of nuclear energy in the average U.S. kWh. For the PP resin, 99.8 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). The renewable energy (0.19 GJ/1000 kg) used at the PP resin plant comes solely from nuclear, hydropower and other renewable sources (geothermal, solar, etc.) from electricity production.

The energy representing natural gas and petroleum used as raw material inputs for the production of propylene used to produce PP resin are included in the cradle-to-incoming material amounts in Table 2. The energy inherent in these raw materials are called material feedstock energy. Of the total energy (75.5 GJ) for 1,000 kg of PP resin, 51.2 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 PP resin. Approximately 68 percent of the total energy is inherent energy in the natural gas and petroleum used as a feedstock to create propylene, which in turn is used to create PP resin. Of the feedstock sources for propylene, 87 percent come from natural gas, while 13 percent of the feedstock sources come from oil.

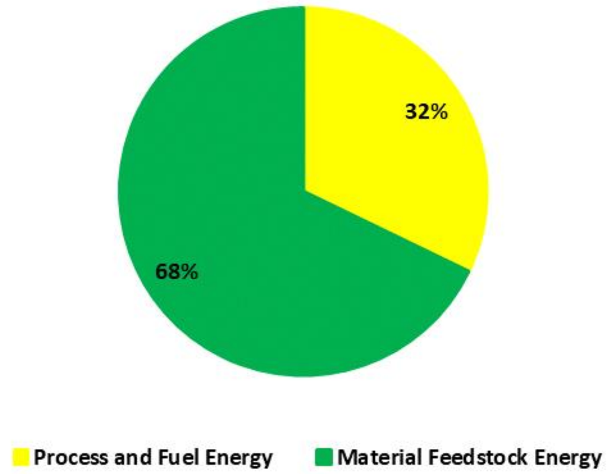

Figure 3. Process/Fuel and Material Feedstock Percentages for PP Resin

Energy Demand by Fuel Type

The total energy demand by fuel type for PP is shown in Table 3 and the percentage mix is shown in Figure 4. Natural gas and petroleum together make up almost 98 percent of the total energy used. As shown in Figure 3, this is partially due to the material feedstock energy used to create the propylene, which is the main input to PP resin. These material feedstock fuels are part of the energy shown in the natural gas and petroleum split out in the following table and figure. The gate-to-gate production energy for PP resin in the following table and figure represents the energy required for transportation of raw materials to PP manufacturers, the energy required to produce the PP resin, and the production of the fuels and nitrogen needed to manufacture the PP.

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 PP resin production shown in Table 3 and Figure 4, 87 percent of the energy used (65.9 GJ/75.5 GJ) is from natural gas. At the PP resin plant, 70 percent of the energy used (3.03 GJ/4.33 GJ) comes from natural gas. Of that natural gas used at the PP resin plant, over 40 percent is combusted on-site, while more than 50 percent is required to create electricity either through the grid or through a nearby cogeneration plant. Petroleum comprises approximately 10 percent (7.76 GJ/75.5 GJ) of the fuel used for the PP resin production system. Three-quarters of the petroleum for the PP plant is combusted to create electricity, while much of the remainder is used to produce the nitrogen used in the process. Most of 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 a 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 PP 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	30.6	27.0	3.32	0.14	0.092	0.0097	0.022
Virgin PP Resin Production	1.86	1.30	0.016	0.29	0.20	0.021	0.029
Total	**32.5**	**28.3**	**3.33**	**0.43**	**0.29**	**0.031**	**0.051**
	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	71.2	62.9	7.72	0.32	0.21	0.023	0.051
Virgin PP Resin Production	4.33	3.03	0.038	0.68	0.46	0.049	0.069
Total	**75.5**	**65.9**	**7.76**	**1.00**	**0.67**	**0.071**	**0.12**
	Percentage of Total						
	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
	%	*%*	*%*	*%*	*%*	*%*	*%*
Cradle-to-Incoming Materials	94.3%	83%	10%	0.4%	0.3%	0.03%	0.07%
Virgin PP Resin Production	5.7%	4.0%	0.1%	0.9%	0.6%	0.06%	0.09%
Total	**100%**	**87%**	**10%**	**1.3%**	**0.9%**	**0.1%**	**0.2%**

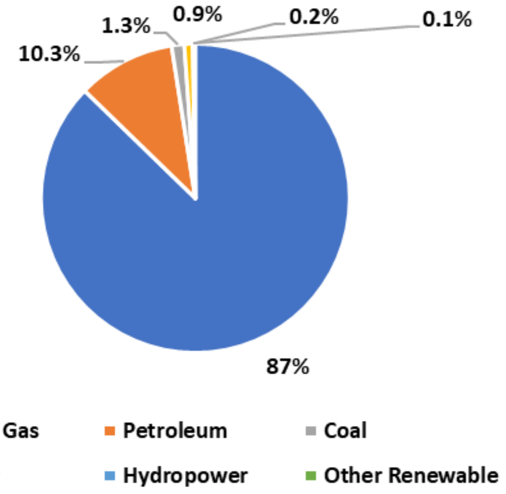

Figure 4. Percentage of Energy Separated by Fuel Type for PP Resin

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 PP 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 that are recycled/reused or land applied are not included as solid wastes, and no credit is given. 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 PP 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 cradle-to-incoming materials and the PP plant. As shown in Figure 5, only 21 percent of the total solid waste is created during the PP resin unit process. Three-quarters of this amount comes from fuels combusted for the electricity used in the plant or for nitrogen production, while only 4 percent of the gate-to-gate PP plant amount is process solid waste.

The majority of solid waste, 79 percent, comes from the production of incoming materials used to produce PP resin. Approximately 87 percent of the raw materials used to create olefins are a product of natural gas processing, with the remaining 13 percent of those raw materials from crude oil refining products. Overall, the solid wastes associated with oil and natural gas extraction make up almost 60 percent of the total solid wastes. The olefins plant process wastes make up approximately 12 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, about half comes from the olefins plant and half comes from the PP plant.

Table 4 also provides a breakout of the total solid wastes by the disposal fate. Of the hazardous waste, 92 percent is incinerated without energy capture, while much of the remainder is sent to waste-to-energy. Focusing specifically on the non-hazardous solid waste produced, 91 percent of the non-hazardous solid waste is landfilled, while much of the remainder is incinerated without energy capture.

Table 4. Total Solid Wastes for PP 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	50.7	0	1.35	0.0035	1.35	5.9E-04	5.78	43.6	49.3
Virgin PP Resin Production	13.5	0.12	0.005	0.0010	0.13	0	0	13.4	13.4
Total	**64.2**	**0**	**1.35**	**0.0045**	**1.48**	**5.9E-04**	**5.78**	**57.0**	**62.8**
	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	50.7	0	1.35	0.0035	1.35	5.9E-04	5.78	43.6	49.3
Virgin PP Resin Production	13.5	0.12	0.005	0.0010	0.13	0	0	13.4	13.4
Total	**64.2**	**0.12**	**1.35**	**0.0045**	**1.48**	**5.9E-04**	**5.78**	**57.0**	**62.8**
	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	79%	0%	2.1%	0.006%	2.1%	0.001%	9.0%	68%	77%
Virgin PP Resin Production	21%	0.2%	0.0%	0.002%	0.2%	0%	0%	21%	21%
Total	**100%**	**0.2%**	**2.1%**	**0.01%**	**2.3%**	**0.001%**	**9.0%**	**89%**	**98%**

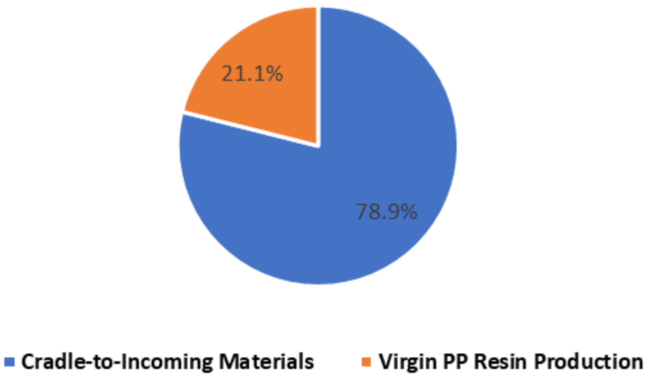

Figure 5. Percentage of Total Solid Wastes for PP Resin System

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 PP resin production are shown in Table 5 and Figure 6. The greatest portion of consumption of water within the PP resin comes from the cradle-to-incoming materials (58 percent). When looking at the individual unit processes, about 37 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 PP resin average data also includes some plants that release water to a different watershed. The PP resin plant water consumption makes up one-third of the total and the water consumed during natural gas extraction and processing comprises almost 14 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 12 percent of the total water consumption. The remaining water consumption comes from the refining of crude oil and production of other fuels used.

Table 5. Water Consumption for PP Resin

	Total Water Consumption		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	Gallons	*Liters*	*%*
Cradle-to-Incoming Materials	635	5,300	58%
Virgin PP Resin Production	459	3,826	42%
Total	**1,094**	**9,126**	**100%**

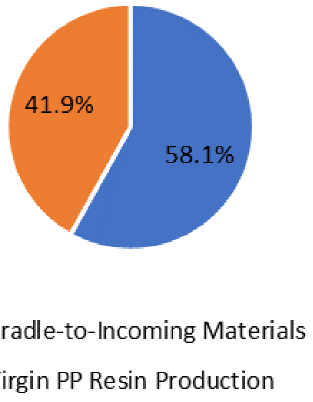

Figure 6. Water Consumption for PP Resin

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. Greenhouse gas emissions are mainly from combustion. In the primary data collected for olefins and PP 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.

The 100-year global warming potential (GWP) factors for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2013[18] 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.

In Table 6 and Figure 7, the life cycle GWP results for the PP resin system are displayed. Of the total, 82 percent of the GWP are attributed to emissions from the incoming materials, including natural gas and petroleum input materials and olefins (propylene) production, with the remaining associated with the production of the PP resin. The largest amount of the GWP is created by the production of propylene, which accounts for 45 percent of the total GWP, which comes directly from the release of greenhouse gases at the olefins plant, much of this from flares. About 19 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 is one-quarter of the total GWP. The process greenhouse gases released at the PP resin plants are less than 1 percent of the total; this is due to flaring, which is considered a mix of process and fuel-based emissions.

---

[18] 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 PP 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	1,275	1,275	82%
Virgin PP Resin Production	273	273	18%
Total	**1,548**	**1,548**	**100%**

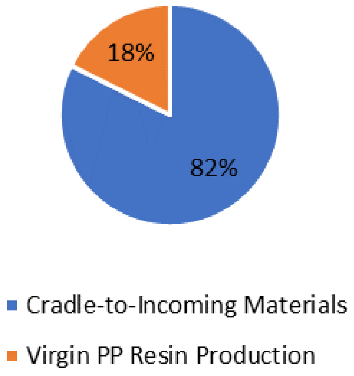

Figure 7. Global Warming Potential for PP Resin

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.[19,20]

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.

---

[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.

[20] 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 PP resin system. Results are shown graphically in Figure 8. In the AP category, 18 percent of the AP is coming from PP resin production and about 82 percent comes from the raw and intermediate material unit processes. Most of the AP amount (69 percent) comes from the extraction and processing of natural gas for materials and fuels, which is used to create 87 percent of the material inputs to the propylene input. Sixteen percent, comes from the combustion of coal for electricity. Almost 5 percent of the AP results come from emissions related to the production of propylene. Less than 1 percent of the total AP comes directly from the PP resin production. The greatest part of the 18 percent AP shown in Table 7 for virgin PP resin production comes from electricity, fuel combustion or transport, with much of the rest coming from the nitrogen production.

Table 7. Acidification Potential for PP Resin

	Acidification Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb SO2 eq	***kg SO2 eq***	***%***
Cradle-to-Incoming Materials	3.94	3.94	82%
Virgin PP Resin Production	0.87	0.87	18%
Total	**4.81**	**4.81**	**100%**

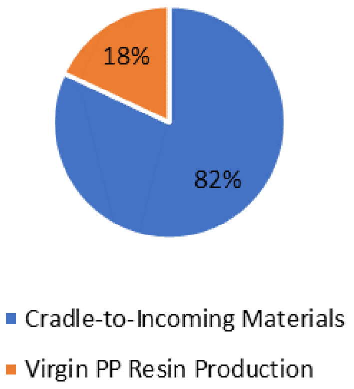

Figure 8. Acidification Potential for PP Resin

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.[21] The TRACI characterization factors for eutrophication are the product of a nutrient factor and a transport factor.[22] 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 PP resin are shown in Table 8 and illustrated in Figure 9. The largest portion, over 90 percent, of the EP results come from the raw and intermediate materials used to create PP resin. The extraction of natural gas for materials and fuels releases approximately 69 percent of the emissions related to the EP impact. The propylene plant process emissions comprise 14 percent of the EP impact results. The gate-to-gate PP resin production generates 10 percent of the EP impact, with more than half of that percentage representing the combustion of fuels for electricity and over 20 percent from the combustion of natural gas in boilers. Only 1 percent of the total EP impact comes from process emissions released at the PP plant.

Table 8. Eutrophication Potential for PP Resin

	Eutrophication Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb N eq	***kg N eq***	***%***
Cradle-to-Incoming Materials	0.24	0.24	90%
Virgin PP Resin Production	0.026	0.026	10%
Total	**0.26**	**0.26**	**100%**

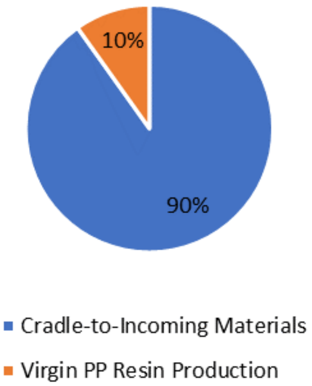

Figure 9. Eutrophication Potential for PP Resin

---

[21] 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.

[22] 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 PP 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 PP resin system, which are also shown graphically in Figure 10. Ozone depletion results for the PP resin system are dominated by the crude oil extraction and refining system at the propylene plant, contributing 99.4 percent of the total ozone depletion impacts. The amount of the ODP shown as PP resin production is from the production of petroleum-based fuels used within the plant. No emissions impacting ODP are released at the PP plants. The 0.6 percent impact coming from PP resin production is for the production of the petroleum fuels used in electricity and transport.

Table 9. Ozone Depletion Potential for PP 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	1.7E-06	1.7E-06	99.4%
Virgin PP Resin Production	1.0E-08	1.0E-08	0.6%
Total	**1.8E-06**	**1.8E-06**	**100%**

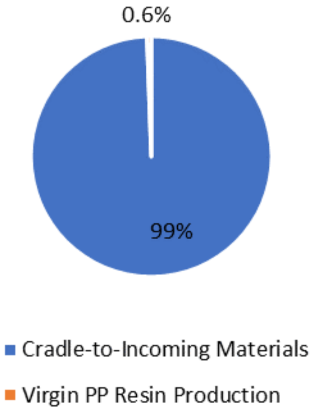

Figure 10. Ozone Depletion Potential for PP Resin

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.[23] Smog formation impact are generally dominated by emissions associated with fuel combustion, so that impacts are higher for life cycle stages and components that have higher process fuel and transportation fuel requirements. In this case, NO_x makes up 96 percent of the smog formation emissions, with VOCs consisting of over 3 percent.

Smog formation potential results for PP resin are displayed in Table 10 and illustrated in Figure 11. Approximately 89% of the POCP impact results comes from the raw and intermediate materials (cradle-to-propylene). The olefins plant releases just 6 percent of the total emissions resulting the POCP. Three-quarters of the remainder of the total POCP impact results are from the natural gas extraction and processing. Smaller amounts are also created from the combustion of coal and the extraction of oil.

The remaining 11 percent of the POCP impact results is released from the PP resin production process. Of that percentage, almost 60 percent of the POCP for the PP 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. Approximately 1 percent of the total emissions resulting in the POCP impact results are released at the PP resin plant as process emissions. The remaining percentage in the PP resin production comes from combustion of natural gas, production of nitrogen, or transport of incoming materials.

Table 10. Photochemical Smog Formation Potential for PP 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	114	114	89%
Virgin PP Resin Production	14.1	14.1	11%
Total	**128**	**128**	**100%**

---

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

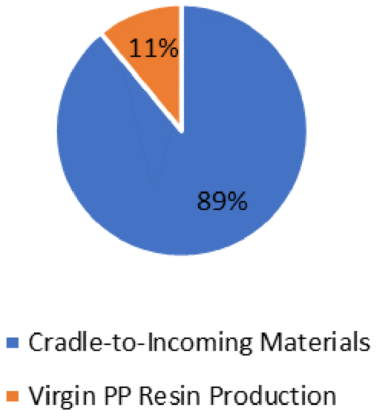

Figure 11. Photochemical Smog Formation Potential for PP Resin

COMPARISON OF 2021 AND 2011 LCI AND LCIA PP RESULTS

This section provides a comparison of life cycle inventory and impact assessment category results that were included in the original virgin PP resin system[24] 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 2021 PP resin results in both English and SI units and includes the percent difference for each category. Percent difference between systems, discussed further below, is defined as the difference between energy totals divided by the average of the two system totals. The results in Table 11 show a decrease in all categories. Note that in some cases, the decrease is small enough not to be considered significantly different. Comparisons of these results have been analyzed in this section focusing on the main differences causing the change in each category. It should be noted that all figures in this section provide a percent increase or decrease above the comparable bars, which is calculated as the difference between the totals divided by the 2011 value.

Based on the uncertainties in LCI energy data, energy differences between systems are not considered meaningful unless the percent difference between system results is greater than 10 percent. The threshold guidelines are not intended to be interpreted as rigorous statistical uncertainty analysis, but rather are provided as general guidelines for readers to use when interpreting differences in system results, to ensure that undue importance is not

---

[24] 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.

placed on small differences that fall within the uncertainties of the underlying data. The solid waste and GWP, which includes factors used to weight and convert the GHG emissions released to an impact category, require a minimum 25 percent difference to consider results significantly different.

Broadly, results differences between the two averaged datasets are predominantly due to the use of additional companies and manufacturing plants when updating the propylene and PP 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. In the updated data, PP resin and propylene are representative of the years 2015 and 2016. For propylene and PP, some of the same plants provided data; however, some of the plants in the current average were not included in the original data collection in 2004-2006. Additional plants participated in the data collection for this update for the olefins. Also, the number of companies participating in this update for the PP resin remained at 3; however, only one plant that participated in collecting data for the previous analysis provided data for 2015-2016.

Table 11. Comparison of 2011 and 2021 LCI and LCIA Results for Virgin PP Resin

	1000 pounds of Virgin Polypropylene 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***
PP 2021	32.5	32.4	0.08	62.8	1,548
PP 2011	33.1	33.0	0.12	85.0	1,860
	1000 kilograms of Virgin Polypropylene 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***
PP 2021	75.5	75.3	0.19	62.8	1,548
PP 2011	77.0	76.6	0.28	85.0	1,860
Percent Difference	2%	2%	39%	30%	18%

*Total Solid Waste excludes hazardous solid waste for 2021 as this category was not included as Solid Waste in 2011.

ENERGY COMPARISON

Overall, the total energy for PP resin has decreased 1.5 GJ on a 1,000 kg basis (0.6 MMBtu/1,000 lb). There is a 2 percent difference in total energy as compared to the original results. This percentage is small and would not be considered significantly different due to differences in the plants. When comparing the PP resin unit process average energy data, data from the plant that were collected for both studies did decrease on this same magnitude with some energy sources increasing by small amounts while others decreased by about the same amount. Certainly, the addition of different 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.

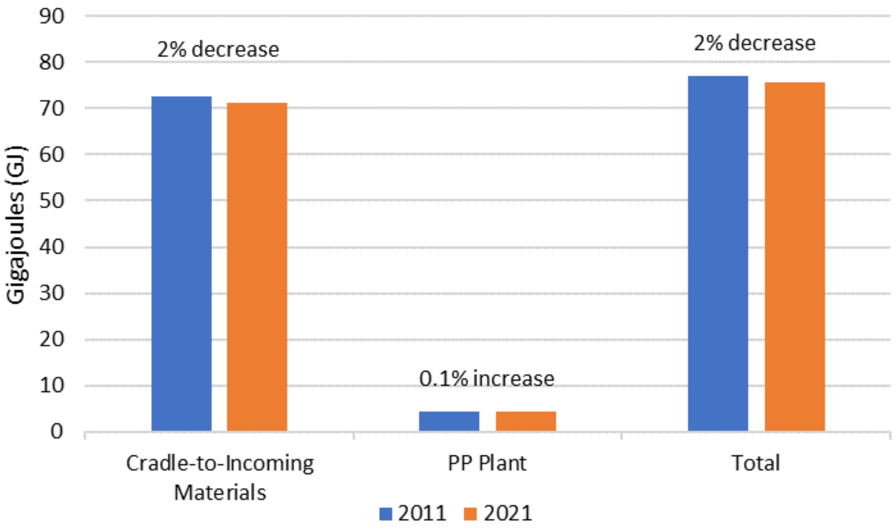

Figure 12. Decrease in Energy by Stage per 1,000 kg (GJ)

The energy of material resource, which pertains to the amount of inherent energy from the raw materials increased by a small amount for PP resin due to the slight increased amount of propylene input to the PP process compared to the data in the 2011 report. As the amount of material resource energy increased, but the total energy still decreased, it can be concluded that the difference in process energy decreased more than the 2 percent shown in the total. It can also be concluded that this decrease is due to the energy decreases in the energy requirements for the olefins plants, as well as the oil and natural gas extraction and processing/refining. The energy for converting propylene to PP resin increased by 0.1 percent compared to the 2004-2006 energy for this process. This does not mean that efficiency has not improved, since 2 of the 3 plants in the current analysis were not in the original analysis. The fact that the current average energy usage is very similar to the previous average energy usage, even with different plants participating, suggests that the data provide a good representation of average North American production.

The difference in renewable energy decreased about 33 percent from the original results. Although this seems quite large, the renewable energy makes up less than one percent of the total energy. Almost all of the renewable energy comes from the production of electricity. The U.S. average electricity grid was used for both the original study and the current update. Of the 2006 electricity grid, approximately 8 percent was created by renewable energy, whereas this renewable energy percentage has almost doubled in 2015 to 15.7 percent. Even though renewable source use has increased in the U.S. average electricity grid, the use of electricity in all processes required to manufacture PP has decreased. This decrease in the use of renewable energy is mainly due to decreases in the use of electricity (hydropower and other renewable resources for energy) within all processes required to manufacture PP.

SOLID WASTE COMPARISON

When compared to the 2011 PP resin total solid waste amount, the current PP resin study shows 22 kg per 1000 kg PP resin less solid waste, which is a 30 percent difference and is considered a lower amount from the original study. Much of this decrease is due to the differences in propylene and PP plant data collected between the 2011 and 2021 reports. Figure 13 provides a visual of the total solid waste amount split out by the PP unit process and cradle-to-incoming materials. A decrease occurs for both cradle-to-incoming materials and at the PP plant. Comparing the current process solid waste at the PP plant to the 2011 solid waste, a decrease is seen, but the largest decrease in solid waste at the PP plant comes from the fuel use. This is possibly due to the decrease in coal use in the electricity grid used in 2016 as compared to the previous grid used. The decrease in cradle-to-incoming materials (olefins) is also mainly due to an overall decrease in the electricity use of the olefins plant 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.

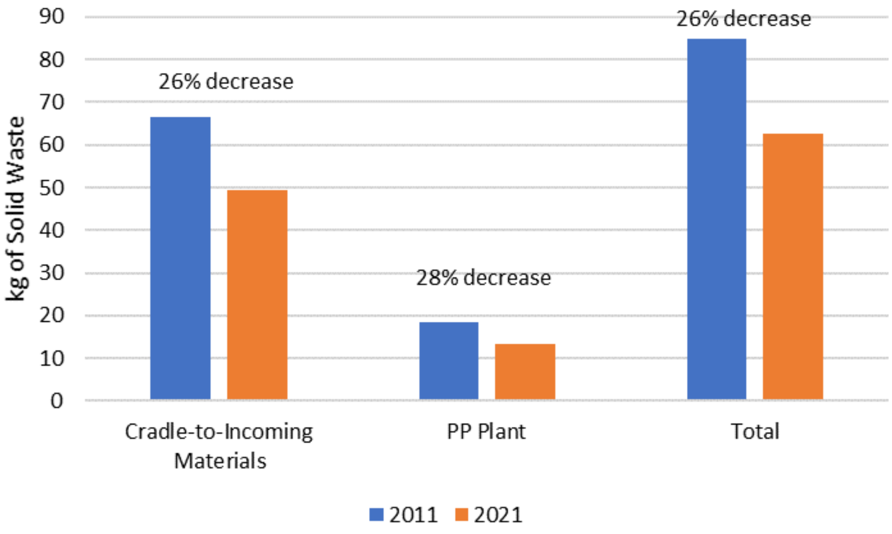

Figure 13. Decrease in Solid Waste Weight by Unit Process (kg Per 1,000 kg)

GLOBAL WARMING POTENTIAL COMPARISON

The global warming potential decreased by 312 kg CO_2 equivalents/1000 kg PP resin, which calculates to an 18 percent difference. This percent difference is lower than the 25 percent limit and is not considered sizable enough to signify a definite difference in results. Figure 14 displays a column chart with the PP resin and cradle-to-incoming materials results that makeup the decrease when comparing the 2011 and 2021 GWP results. Although this seems like a large decrease compared to the decrease in energy, this overall decrease follows the trend shown in total energy, since much of the greenhouse gases are created from fuel production. The total energy amount includes the material resource energy, which has no greenhouse gases associated with it as it is not combusted.

Looking at the process/transport energy only, the percent decrease is about 16 percent. The GWP specific to the PP resin plant decreases by 1 percent, while the energy for the plant actually increased by a fraction of a percentage. This decrease is so small that it can be considered as equivalent to the previous amounts due to higher uncertainty. This higher uncertainty comes from the use of an order of magnitude in the updated GHG emissions compared to calculated averages of GHG emissions in the original data. To clarify, in the 2011 report, carbon dioxide and methane were available as calculated average amounts due to the provision of these data by all three PP plants. In the current PP LCI data, the amounts of carbon dioxide and methane were not available for one of the plants and so an order of magnitude was used for the average of each of these emissions. The decrease in GWP for olefins comes from decreases in energy use for the raw materials and for the olefins plant. The amount of coal combusted for the US average electricity grid has decreased over time with an increase in natural gas combustion. Coal production and combustion releases higher amounts of greenhouse gases compared to natural gas production and combustion.

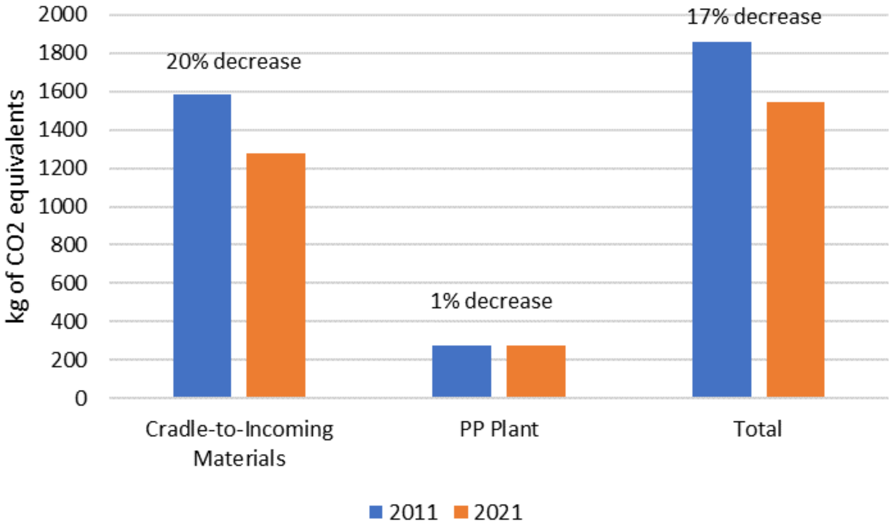

Figure 14. Decrease in Global Warming Potential by Unit Process (kg of CO2 eq. per 1,000 kg)

APPENDIX: POLYPROPYLENE (PP) MANUFACTURE

This appendix discusses the manufacture of polypropylene (PP) resin. PP is used to manufacture carpet, food containers, and parts for various industries. More than 17,153 million pounds of PP was produced in the U.S. and Canada in 2015 (ACC, 2016). The material flow for PP resin is shown 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 process is included in this appendix:

- Polypropylene resin production

LCI data for olefins (propylene) and PP 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, 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 the ancillary input material, nitrogen, were adapted from the ecoinvent 3 database. This dataset is not available due to confidentiality issues of that database. The adaptation included the use of the US electricity grid and US transportation.

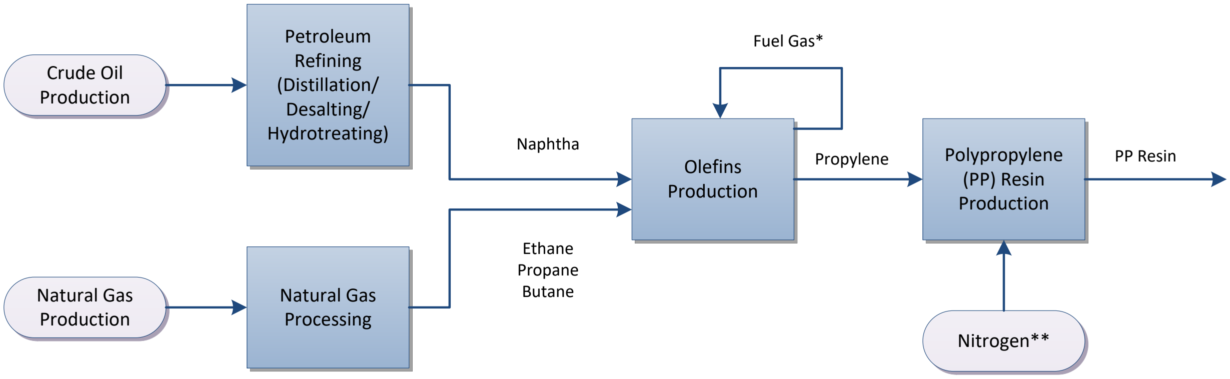

Figure 15. Flow diagram for the Production of Polypropylene (PP) Resin.

* Fuel gas used for energy is created from off-gas produced in the process.
** Nitrogen data is from ecoinvent and is adapted to U.S. conditions. Nitrogen is an ancillary material input.

POLYPROPYLENE (PP) PRODUCTION

The two main technologies used to manufacture polypropylene are the bulk slurry and the gas-phase processes. Spheripol, a type of bulk slurry technology, and Unipol, a type of gas-phase technology are used by the data providers. According to an article on Plastics Insight, of the world production of PP resin, 39 percent of PP resin manufacturers used Spheripol, while 16 percent of PP manufacturers used the Unipol technology. A number of other patented technologies are used at a lower percentage. No information was found about the representative of those percentages within North America.

In the bulk slurry technology, polymerization is carried out in liquid propylene in tubular loop reactors (Chem Eng, Sept, 2013). Catalysts and liquid propylene are continually fed into a prepolymerization reactor, then sent to a series of bulk loop reactors to form PP granules. Small amounts of hydrogen are added to control PP properties. Any excess propylene monomer is removed from the polymer granules using vaporization operations (Lyondellbasell). The monomer stream is purified and recycled to the reactor. The remaining PP granules are then sent to extrusion for pelletization (Ind Contacts, 2018).

The gas-phase technology uses a fluidized bed reactor framework (Chem Eng, May, 2013). The propylene feedstock is degassed to rid it of any oxygen or other unwanted materials. The feedstock is then cooled and sent to a dryer before it is sent to the gas-stage polymerization reactor. Small amounts of hydrogen are added to control the properties of the PP. The polymer is taken out intermittently from the reactor using separators. The excess monomer propylene is recycled back to the reactor. The polypropylene is removed from the separators as a powder. These PP granules are sent to extrusion for pelletization (Ind Contacts, 2018).

LCI data for the production of PP resin were collected from three producers (three plants) in North America –all from the United States only. 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 PP resin production amount is approximately 16 percent of the PP resin production in the U.S. in 2015 (ACC, 2016). Only small amounts of off-spec and trim product are coproducts of PP resin production, and a mass basis was used to allocate the environmental burdens among the coproducts.

PP resin producers from the United States provided data from their facilities using technology ranging from average to state-of-the-art. Approximately two-thirds of the total PP resin produced by the data providers come from the bulk slurry process, while the remainder is gas phase.

Primary data were collected from PP 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 their company for PP production in North America.

Data providers reviewed their data as well as the average PP 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 PP 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 12. LCI Data for the Production of Polypropylene (PP)

	1,000 lb		1,000 kg		
Material Inputs					
Propylene	1,014	lb	1,014	kg	
Nitrogen	64.0	lb	64.0	kg	
Energy					
Process Energy					
Electricity from grid	72.6	kWh	160	kWh	
Electricity from cogen	63.5	kWh	140	kWh	
Natural gas	545	ft^3	34.0	m^3	
Avoided Energy					
Natural gas avoided due to export of vent gas	43.3	ft^3	2.70	m^3	
Transportation Energy					
Pipeline -refinery products	11.8	ton·mi	38.0	tonne·km	
Environmental Emissions					
Atmospheric Emissions					
Carbon dioxide, fossil	10.0	lb	10.0	kg	*
NMVOC, non-methane volatile organic compounds,	0.11	lb	0.11	kg	
Particulates, unspecified	0.010	lb	0.010	kg	*
Particulates, < 2.5 um	0.0090	lb	0.0090	kg	
Particulates, > 2.5 um, and < 10um	0.016	lb	0.016	kg	
Sulfur oxides	0.0010	lb	0.0010	kg	*
Nitrous oxide	1.0E-04	lb	1.0E-04	kg	*
Methane	0.0010	lb	0.0010	kg	*
Aldehydes, unspecified	0.010	lb	0.010	kg	*
Carbon monoxide	0.010	lb	0.010	kg	*
Ammonia	0.0010	lb	0.0010	kg	*
Nitrogen oxides	0.044	lb	0.044	kg	
Waterborne Releases					
BOD5, Biological Oxygen Demand	0.010	lb	0.010	kg	*
COD, Chemical Oxygen Demand	0.010	lb	0.010	kg	*
Suspended solids, unspecified	0.013	lb	0.013	kg	
Zinc	1.0E-06	lb	1.0E-06	kg	*
Fluoride	1.0E-06	lb	1.0E-06	kg	*
Dissolved solids	1.0E-04	lb	1.0E-04	kg	*
Cyanide	1.0E-06	lb	1.0E-06	kg	*
Solid Wastes					
Solid waste, process to landfill	0.42	lb	0.42	kg	
Solid Waste Sold for Recycling or Reuse	0.70	lb	0.70	kg	
Hazardous waste to landfill	0.0010	lb	0.0010	kg	
Hazardous waste to incineration	0.0051	lb	0.0051	kg	
Hazardous waste to WTE	0.12	lb	0.12	kg	
Water Consumption	360	gal	3,000	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.

Source: Primary Data, 2020

REFERENCES

American Chemistry Council (2016), Resin Review 2016.

Chem Eng (May 2013) *Propylene Production via Gas-Phase Process*. Chemical Engineering. May 1, 2013.

Chem Eng (Sept 2013). *Propylene Bulk Phase Process.* Chemical Engineering. September 1, 2013

Ind Contacts (2018). Discussions of the process with PP data providers. 2018.

Lyondellbasell. Lyondellbasell brochure from www.lyondellbasell.com/technology. Accessed 2020.

Plastics Insight. *All About Polypropylene (PP): Production, Price, Market & its Properties.* Available at https://www.plasticsinsight.com/resin-intelligence/resin-prices/polypropylene/

Primary Data (2020). Primary data from 2015-2016 collected from 3 PP producers by Franklin Associates. 2017-2020