CRADLE-TO-GATE LIFE CYCLE ANALYSIS OF HIGH IMPACT POLYSTYRENE (HIPS) RESIN

Final Report

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Submitted by:

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PREFACE

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

This report was prepared for ACC by Franklin Associates, A Division of Eastern Research Group (ERG), Inc. as an independent contractor. This project was managed by Melissa Huff, Senior LCA Analyst and Project Manager, who was also lead for modeling and report writing. Anne Marie Molen assisted with data collection tasks and report/appendix preparation. Mariya Absar and 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: Americas Styrenics LLC, INEOS Styrolution America LLC, TotalEnergies Petrochemical & Refineries USA, Inc. and SABIC who graciously provided primary Life Cycle Inventory data for HIPS 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.

June, 2022

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LIST OF ACRONYMS

(Alphabetical)

ACC	THE AMERICAN CHEMISTRY COUNCIL
AP	ACIDIFICATION POTENTIAL
BOD	BIOCHEMICAL OXYGEN DEMAND
COD	CHEMICAL OXYGEN DEMAND
CFC	CHLOROFLUOROCARBON
DOE	DEPARTMENT OF ENERGY
EGRID	EMISSIONS & GENERATION RESOURCE INTEGRATED DATABASE
EIA	ENERGY INFORMATION ADMINISTRATION
EP	EUTROPHICATION POTENTIAL
ERG	EASTERN RESEARCH GROUP, INC
EQ	EQUIVALENTS
GHG	GREENHOUSE GAS
GJ	GIGAJOULE
HCFC	HYDROCHLOROFLUORCARBON
HIPS	HIGH IMPACT POLYSTYRENE
GREET	GREENHOUSE GASES, REGULATED EMISSIONS, AND ENERGY USE IN TECHNOLOGIES
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
MM	MILLION
NAPAP	NATIONAL ACID PRECIPITATION ASSESSMENT PROGRAM
NMVOC	NON-METHANE VOLATILE ORGANIC COMPOUNDS
NREL	NATIONAL RENEWABLE ENERGY LABORATORY

ODP	OZONE DEPLETION POTENTIAL
POCP	PHOTOCHEMICAL SMOG FORMATION (HISTORICALLY PHOTOCHEMICAL OXIDANT CREATION POTENTIAL)
RCRA	RESOURCE CONSERVATION AND RECOVERY ACT
SI	INTERNATIONAL SYSTEM OF UNITS
TRACI	TOOL FOR THE REDUCTION AND ASSESSMENT OF CHEMICAL AND OTHER ENVIRONMENTAL IMPACTS

CRADLE-TO-GATE LIFE CYCLE ASSESSMENT OF HIGH IMPACT POLYSTYRENE (HIPS) RESIN

INTRODUCTION

This study provides the American Chemistry Council (ACC), their members, users of the U.S. LCI Database, and the public at large with information about the life cycle inventory and impacts for the production of high impact polystyrene (HIPS) resin, which is used in a variety of end use applications including appliance parts, food packaging, and other durable applications. 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.

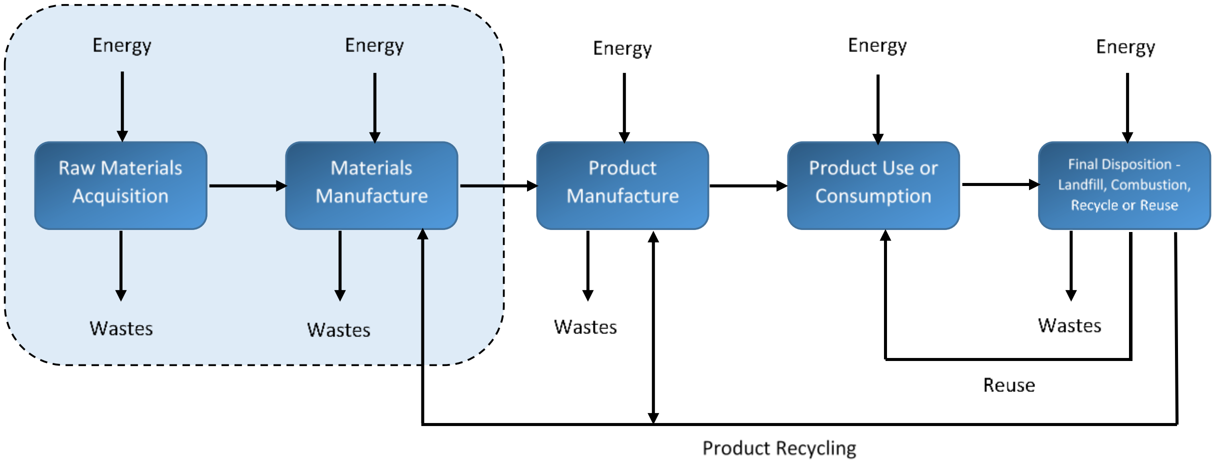

Figure 1. General materials flow for "cradle-to-grave" analysis of a product system. The dashed box indicates the boundaries of this analysis.

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 HIPS resin. It is considered a cradle-to-gate boundary system because this analysis ends with the HIPS resin production. The system boundaries stop at the HIPS 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 or thermoformed products. 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 materials manufacture. 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 ethylbenzene/styrene and HIPS 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 U.S. Department of Energy (DOE) National Renewable Energy Laboratory (NREL) who maintains the U.S. LCI Database.

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

STUDY GOAL AND SCOPE

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

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

[2] Cradle-to-Gate Life Cycle Analysis of Olefins. Franklin Associates. 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 HIPS 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 HIPS resin and
- To provide information about the environmental burdens associated with the production of HIPS resin. The LCA results for HIPS production can be used as a benchmark for evaluating future updated HIPS 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 HIPS resin is its forming into various products, for example, electronics housing or automotive parts. As the study boundary concludes at the HIPS 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 HIPS resin produced.

SCOPE AND BOUNDARIES

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

- Raw material extraction (e.g., extraction of petroleum and natural gas as feedstocks) through styrene, polybutadiene, and mineral oil production, as well as incoming transportation for each process, and
- HIPS resin manufacture, including incoming transportation for each input material.

Because upstream olefin manufacture impacts the results for the production of ethylbenzene and polybutadiene used to produce HIPS, some discussion of ethylene, pyrolysis gas, and butadiene 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 HIPS resin manufacture. Figure 2. presents the flow diagram for the production of HIPS resin. A unit

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

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.

Technological Scope

The technology used to manufacture HIPS in North America begins with the grinding and dissolving of rubber in the presence of the styrene monomer. The rubber solution is transferred to a storage tank, fed to a prepolymerization reactor, and followed by polymerization of styrene in a series of reactors in the presence of initiators. Continuous stirred tank or tubular reactors are used. Following the reactor, the polymer solution is sent for devolatizing where the monomer and solvents are removed from the polymer. The polymer is then pelletized.

The data collection methods for HIPS include direct measurements, information provided by purchasing and utility records, and engineering estimates. The technology represented by the data provided for this study is considered average to state-of-the-art compared to industry practices.

Temporal and Geographic Scope

As part of the data quality assessment, time period and geography were considered. All data submitted for HIPS represent the years 2015 or 2016. For the HIPS resin primary data, companies were requested to provide data for the year 2015, the most recent full year of HIPS resin production prior to the project initiation date. Companies providing data were given the option to collect data from the year preceding or following 2015 if either year would reflect more typical production conditions. Four plants provided data for the year 2015, and one plant provided data for the year 2016. After reviewing individual company data in comparison to the average, each manufacturer verified data from 2015 and/or 2016 was representative of an average year for HIPS resin production at their company.

Ethylbenzene/styrene data was updated using one dataset collected from 2015 and averaging it with the 2002/2003 datasets collected and used in the original average ethylbenzene/styrene LCI data. The older and new datasets were compared, and as needed, questions were asked of the company providing the 2015 data. Overall, the differences in energy and emissions data were small. The data collected for raw material inputs and electricity in 2015 was within 1 percent as compared to the 2002/2003 data. Other energy inputs provided in 2015 were within 6 percent of the older datasets.

The geographic scope of the analysis is the manufacture of HIPS resin in North America. HIPS resin data were collected from plants all located in the United States. Some input materials were modeled using North American databases such as the U.S. LCI database and Franklin Associates' private database. The U.S. electricity grid from 2016 was taken from information in Emissions & Generation Resource Integrated Database (eGRID) 2016 database.

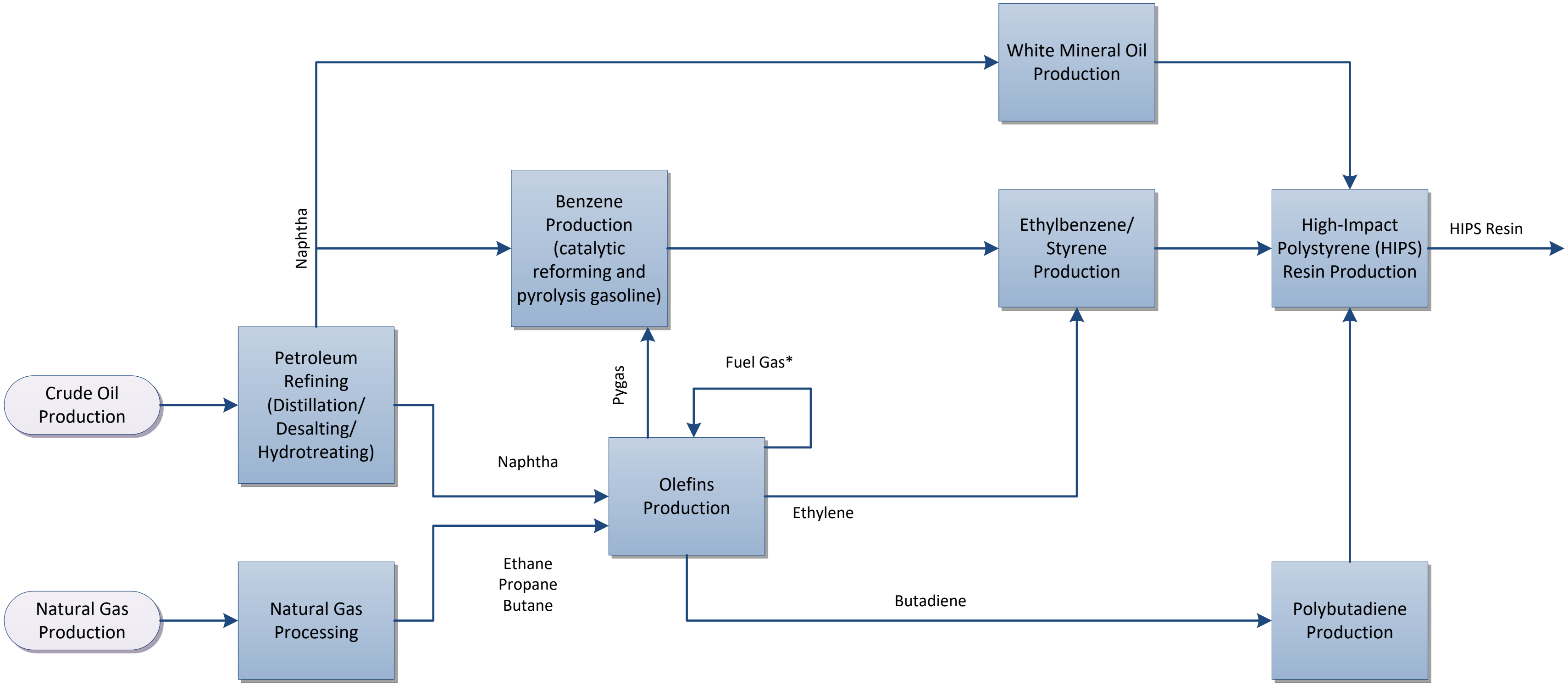

Figure 2. Flow diagram for the Production of High impact polystyrene (HIPS) Resin.

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

Exclusions from the Scope

The following are not included in the study:

- **Miscellaneous materials and additives.** Selected materials such as catalysts, initiators, ancillary materials, or other additives which total less than one percent by weight of the net process inputs are typically not included in assessments. This follows the ISO cut-off criteria rules in ISO 14040 and 14044. 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 exceptionally 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 substantial 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 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.[4] 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.[5] In addition, the following LCI results are included in the results reported in the analysis:

- Energy demand is a cumulative inventory of all forms of energy used for processing energy, transportation energy, and feedstock energy. This analysis reports total energy demand, with renewable and non-renewable energy demand reported separately to assess consumption of fuel resources that can be depleted. 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. Consumed water does include removal of water from one watershed to another.

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[4] 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.

[5] 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 HIPS resin using the most recent data available for each process. A production-weighted average was calculated for the HIPS resin data (production for the year 2015-2016) collected for this analysis. The ethylbenzene/styrene data is a straight average of the one dataset collected from 2015 plus two datasets used in the original analysis from 2002 and 2003. The benzene data is an average of one dataset from 2003 and two datasets from 1992 representing two types of technology. The olefins data was also calculated as a production-weighted average of primary datasets for 2015. Secondary data was researched in 2017 for crude oil extraction and refining and natural gas production and processing. Secondary sources were used for white mineral oil and polybutadiene, which were updated to use the 2017 crude oil extraction and refining data. All included processes are shown in Figure 2. .

LCI data for the production of HIPS resin were collected from four producers (five plants) in North America within the United States. 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 HIPS resin production amount is approximately 62 percent of the HIPS resin production in North America in 2015[6]. This percentage assumed that the one plant providing data from 2016 produced a similar amount of HIPS resin in 2015. Only small amounts of off-spec product are coproducts of HIPS resin production, and a mass basis was used to allocate environmental burdens among the coproducts.

LCI data for the production of ethylbenzene and styrene were collected from one producer in North America within the United States for the year 2015. In the original ethylbenzene/styrene data, two producers provided data for 2002 and 2003. The older and new datasets were compared, and as needed, questions were asked of the company providing the 2015 data. The data collected for raw material inputs and electricity in 2015 was within 1 percent as compared to the 2002/2003 data. Other energy inputs provided in 2015 were within 6 percent of those of the older datasets. A straight average was calculated from these data collected and used to develop the LCA model. Only a small amount of toluene is produced as a coproduct of the ethylbenzene/styrene production, and a mass basis was used to allocate environmental burdens among the coproducts.

LCI data for the production of olefins, including ethylene used in the manufacture of ethylbenzene/styrene and pyrolysis gasoline used to produce benzene, 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. Ethylene and pyrolysis gasoline are coproducts during olefins production, and a mass basis was used to allocate the environmental burdens among these coproducts.

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

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 HIPS resin is based on the locations where material sourcing and production take place, and (2) representative of current industry practices in these regions. As described in the previous section, four companies each provided current, geographically representative data for all primary HIPS data collected for this LCA.

The incoming material and fuel datasets for HIPS 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 Technologies (GREET) Model or ecoinvent[7]. 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 data sets used were the most current and most geographically and technologically relevant data sets available during the data collection phase of the project.

Consistency, Completeness, Precision: Data evaluation procedures and criteria were applied consistently to all primary data collected from the participating producers. 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 comment on their own data normalized to 1000 pounds as well as the industry average dataset normalized to 1000 pounds.

Representativeness: HIPS resin manufactured in North America is commonly produced using mass polymerization within the United States. The four companies provided data from their facilities using technology ranging from average to state-of-the-art. Most of the producers use continuous stirred tank or tubular reactors, while others stated confidential processes with less detail provided.

The ethylbenzene/styrene monomer process commonly utilizes catalytic alkylation of benzene with ethylene to produce ethylbenzene, which is then dehydrated to create styrene. The data collected for 2015 and the 2002-2003 data are representative of this technology. Data from 2015 was compared with the previous data collected and the differences were small enough to assume no major changes had been made to the technology. The data collected for raw material inputs and electricity in 2015 was within 1 percent as compared

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[7] 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].

to the 2002/2003 data. Other energy inputs provided in 2015 were within 6 percent of those of the older datasets. The 2015 company was also questioned about changes in the process over the past 10 years.

The LCI data for the olefins system is shown in the appendix of a separate report, *Cradle-to-Gate Life Cycle Analysis of Olefins*[8]*.* Primary data were collected from olefin 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 ethylene, butadiene and pyrolysis gasoline (pygas) 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 and white mineral oil 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 HIPS 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 used to develop the most representative average for HIPS 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 for modeling purposes but could not be shown due to confidentiality.

Order of Magnitude: In some cases, emissions data in primary data averages 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.

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

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 HIPS resin, ethylbenzene/styrene, 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. From primary data collected, chemical processes that create coproducts include benzene, styrene, olefins, and HIPS production.

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[9]. In this standard, the preferred hierarchy for handling allocation is (1) avoid allocation where possible, (2) allocate flows based on direct physical relationships to product outputs, (3) use some other relationship between elementary flows and product output. No single allocation method is suitable for every scenario. As described in ISO 14044 section 4.3.4.2, when allocation cannot be avoided, the preferred partitioning approach should reflect the underlying physical relationships between the various 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 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 HIPS resin production. The material coproducts from

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

ethylene production for all plants included propylene, pyrolysis gasoline, butadiene, ethane, hydrogen, acetylene, crude benzene, and lesser amounts of various heavy end products. The material coproduct for styrene monomer included a small amount of toluene. The material coproducts from HIPS resin production include a small amount of off-spec material.

For each process step creating coproducts, 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. Unit process tables in the appendix that show avoided fuels in the energy section have been given system expansion due to an exported coproduct.

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 and Mexico. 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 [10]. The 2016 grid was used for consistency with the age of the collected resin process data. Table 2 provides a breakdown of energy sources and the contribution by percentage of each source to the grid mix.

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

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.

Table 2. Average U.S. 2016 Electricity Grid Mix Profile

	2016 Grid Mix
Renewable Energy Sources	
Geothermal	0.4%
Kinetic (in wind)	5.6%
Solar (converted)	0.9%
Biomass	1.7%
Hydroelectric	6%
Unspecified	0.5%
Total Renewable Energy Sources	15%
Non-Renewable Energy Sources	
Coal (bituminous and lignite)	30%
Natural Gas	34%
Nuclear	20%
Oil Products (diesel and residual)	0.6%
Total Non-Renewable Energy Sources	85%
Total Renewable and Non-Renewable Energy Sources	**100%**

Note: Energy sources may not add to total shown due to rounding. Grid mix percentages do not include average national grid loss of 5.2%.

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 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[11].

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 energy information administration (EIA) fuel consumption and electricity net generation data from cogeneration plants in 2016.[12] 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

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

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

amounts, which was divided by the efficiency and converted to natural gas amounts in cubic feet.

LIFE CYCLE INVENTORY AND IMPACT ASSESSMENT RESULTS

This section presents baseline results for the following LCI and LCIA results for both 1,000 pounds and 1,000 kilograms of HIPS:

Life cycle inventory results:

- Total 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 HIPS:

- Cradle-to-incoming materials – includes the raw materials through the production of polybutadiene, styrene, and mineral oil.
- HIPS resin production – is the gate-to-gate unit process and includes the production of fuels used in the process.

Tables and figures are provided for HIPS 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-HIPS and HIPS system are interchangeable). The phrase “gate-to-gate” is defined as including only the onsite process/fuels.

ENERGY DEMAND

Total Energy Demand

Total 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 a main input to ethylbenzene and polybutadiene used to produce HIPS resin.

The average total energy required to produce HIPS is 38.1 million Btu per 1,000 pounds of HIPS resin or 88.5 gigajoule (GJ) per 1,000 kilograms of HIPS resin. Table 3 shows total energy demand for the life cycle of HIPS resin production. The HIPS resin production energy has been split out from the energy required for incoming materials, including the production of petroleum extraction and refining, natural gas production and processing, olefins (ethylene/pyrolysis gasoline/butadiene), benzene, white mineral oil, polybutadiene, and ethylbenzene/styrene monomer. Only approximately 3 percent of the total energy is required to produce the HIPS resin itself. The remaining 97 percent is used to create the raw and intermediate materials. A little less than 90 percent of the required energy is used to create the needed styrene (cradle-to-styrene), which makes up over 90 percent of the incoming material required to create HIPS resin.

Table 3. Total Energy Demand for HIPS Resin

	Basis: 1,000 pounds		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	MM Btu	***MM Btu***	***MM Btu***
Cradle-to-Incoming Materials	37.0	36.9	0.084
Virgin HIPS Resin Production	1.09	1.06	0.035
Total	**38.1**	**37.9**	**0.12**
	Basis: 1,000 kilograms		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	GJ	***GJ***	***GJ***
Cradle-to-Incoming Materials	86.0	85.8	0.19
Virgin HIPS Resin Production	2.55	2.46	0.082
Total	**88.5**	**88.2**	**0.28**
	Percentage		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	%	***%***	***%***
Cradle-to-Incoming Materials	97.1%	96.9%	0.2%
Virgin HIPS Resin Production	2.9%	2.8%	0.1%
Total	**100%**	**99.7%**	**0.3%**

Non-renewable energy demand includes the use of fossil fuels (petroleum, natural gas, and coal) for process energy, transportation energy, and as material feedstocks (e.g., oil and gas used as feedstocks for the production of the olefins), as well as use of uranium to generate the share of nuclear energy in the average U.S. kWh. For the HIPS resin, 99.7 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 (0.082 GJ/1000 kg) used at the HIPS resin plant comes solely from hydropower and other renewable sources (geothermal, solar, etc.) from electricity production.

The energy content of natural gas and petroleum used as raw material inputs for the production of ethylene, butadiene and pygas used to produce HIPS resin is included in the cradle-to-incoming material amounts in Table 3. The energy inherent in these raw materials is called material feedstock energy. Of the total energy (88.5 GJ) for 1,000 kg of HIPS resin, 52.8 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 HIPS resin. Approximately 60 percent of the total energy is inherent energy in the natural gas and petroleum used as a feedstock to create olefins, benzene and white mineral oil, which in turn are used to create HIPS resin. Of the feedstock sources for ethylene, butadiene, and pygas, approximately 90 percent comes from natural gas, while 10 percent of the feedstock sources come from oil. Although a majority of the feedstock split for olefins is natural gas, a majority of the feedstock for benzene and white mineral oil come from oil. Overall, the energy of material resource has a split of approximately 51 percent from natural gas and 49 percent from oil.

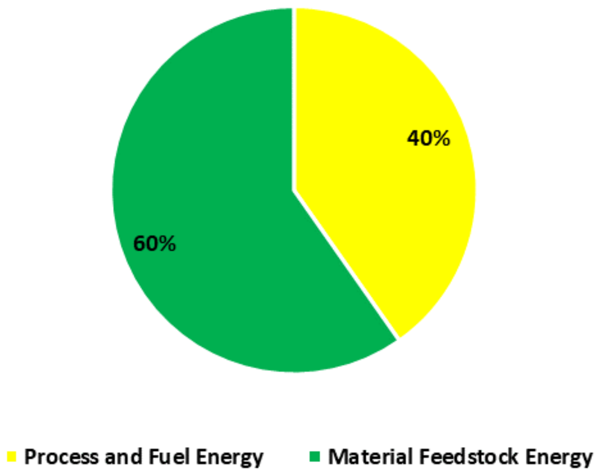

Figure 3. Process/Fuel and Material Feedstock Percentages for HIPS Resin

Energy Demand by Fuel Type

The total energy demand by fuel type for HIPS is shown in Table 4 and the percentage mix is shown in Figure 4. Natural gas and petroleum together make up 97 percent of the total energy used. As shown in Figure 3, this is partially due to the material feedstock energy used to create the olefins, benzene, and white mineral oil, all of which are intermediate or direct inputs to HIPS 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 HIPS resin in the following table and figure represents the energy required for transportation of raw materials to HIPS manufacturers, the energy required to produce the HIPS resin, and the production of the fuels combusted during the HIPS resin manufacture.

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 HIPS resin production shown in Table 4 and Figure 4, 64 percent of the energy used (56.6 GJ/88.5 GJ) is from natural gas. At the HIPS resin plant, 50 percent of the energy used (1.27 GJ/2.55 GJ) comes from natural gas. Of that natural gas used at the HIPS resin plant, over 56 percent is combusted on-site, while 43 percent is required to create electricity through the grid. Petroleum comprises approximately 33 percent (29.0 GJ/88.5 GJ) of the fuel used for the HIPS resin production system. Almost 93 percent of the petroleum used for the HIPS plant is combusted during transport of materials to the plant. The coal use shown is almost fully from combustion 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 U.S. 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 4. Energy Demand by Fuel Type for HIPS 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	37.0	23.8	12.3	0.46	0.31	0.033	0.052
Virgin HIPS Resin Production	1.09	0.55	0.16	0.21	0.14	0.015	0.021
Total	**38.1**	**24.3**	**12.5**	**0.67**	**0.45**	**0.048**	**0.073**
	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	86.0	55.4	28.6	1.07	0.72	0.076	0.12
Virgin HIPS Resin Production	2.55	1.27	0.37	0.49	0.33	0.035	0.049
Total	**88.5**	**56.6**	**29.0**	**1.55**	**1.04**	**0.11**	**0.17**
	Percentage of Total						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	%	***%***	***%***	***%***	***%***	***%***	***%***
Cradle-to-Incoming Materials	97.1%	62.5%	32.3%	1.2%	0.8%	0.09%	0.14%
Virgin HIPS Resin Production	2.9%	1.4%	0.4%	0.6%	0.4%	0.04%	0.06%
Total	**100%**	**64%**	**33%**	**1.8%**	**1.2%**	**0.1%**	**0.2%**

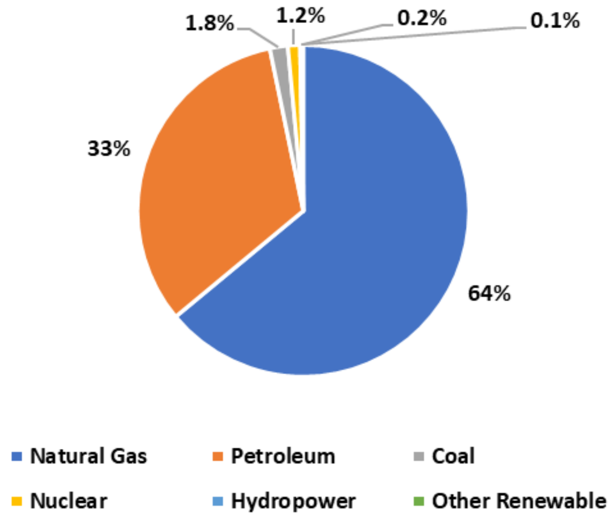

Figure 4. Percentage of Energy Separated by Fuel Type for HIPS Resin

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 resin (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 HIPS resin are included in this analysis as the boundaries end with resin production and do not include production, use, or disposal of products made from the resin.

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 HIPS resin system are shown in Table 5 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 HIPS plant. As shown in Figure 5, only 12 percent of the total solid waste is associated with the HIPS resin unit process. Seventy-seven percent of this amount comes from fuels combusted for the electricity used in the plant, while only 17 percent of the gate-to-gate HIPS plant amount is process solid waste.

The majority of solid waste, 88 percent, comes from the production of incoming materials used to produce HIPS resin. Natural gas and crude oil extraction with refining/processing are used to create the main input materials used in HIPS resin. The solid wastes created from the extraction and processing of these raw materials create 58 percent of the solid wastes from the cradle-to-incoming materials. The coal extraction and combustion for the production of electricity accounts for 30 percent of the solid waste from incoming materials. The olefins and ethylbenzene/styrene plant process wastes make up only 6 percent of the solid wastes of the incoming materials.

Solid wastes are shown separated by hazardous and non-hazardous wastes in Table 5. 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 resource conservation and recovery act (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 1.4 percent of the total solid wastes were considered hazardous wastes. Of that percentage, a little more than 60 percent comes from the olefins plant and most of the remaining amount coming from the HIPS plant.

Table 5 also provides a breakout of the total solid wastes by the disposal fate. Of the total hazardous waste, only one percent is landfilled, while two-thirds of the remaining is incinerated without energy capture, and the remaining third is sent to waste-to-energy. Focusing specifically on the non-hazardous solid waste produced, 95 percent of the non-hazardous solid waste is landfilled, while much of the remainder is incinerated without energy capture.

Table 5. Total Solid Wastes for HIPS 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	77.1	0	0.73	0.011	0.74	3.2E-04	3.28	73.1	76.3
Virgin HIPS Resin Production	11.0	0.38	0.079	0.000	0.46	0.59	0	9.94	10.5
Total	**88.1**	**0.38**	**0.81**	**0.011**	**1.20**	**0.59**	**3.28**	**83.0**	**86.9**
	Basis: 1,000 kilograms								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	kg	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*
Cradle-to-Incoming Materials	77.1	0	0.73	0.011	0.74	3.2E-04	3.28	73.1	76.3
Virgin HIPS Resin Production	11.0	0.38	0.079	0.000	0.46	0.59	0	9.94	10.5
Total	**88.1**	**0.38**	**0.81**	**0.011**	**1.20**	**0.59**	**3.28**	**83.0**	**86.9**
	Percentage of Total								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	%	*%*	*%*	*%*	*%*	*%*	*%*	*%*	*%*
Cradle-to-Incoming Materials	88%	0%	0.8%	0.013%	0.8%	0.000%	3.7%	83%	87%
Virgin HIPS Resin Production	12%	0.4%	0.1%	0.000%	0.5%	0.7%	0%	11%	12%
Total	**100%**	**0.4%**	**0.9%**	**0.01%**	**1.4%**	**0.7%**	**3.7%**	**94%**	**99%**

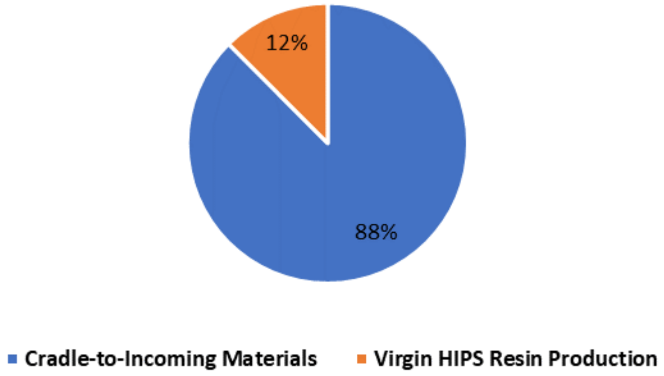

Figure 5. Percentage of Total Solid Wastes for HIPS Resin System

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 HIPS resin production are shown in Table 6 and Figure 6. The greatest portion of consumption of water within the HIPS resin system process comes from the cradle-to-incoming materials (86 percent). When looking at the individual unit processes, the natural gas extraction and processing and crude oil refining account for almost 36 percent of the total water consumption for HIPS resin production. Another large contributor for water consumption is the electricity used during all the processes due to evaporative losses in the use of hydropower, which makes up approximately 27 percent of the total water consumption for the HIPS resin system. The olefins unit process consumes 32 percent of the total water consumption for the HIPS resin system. Some of this water consumption amount at the olefins plants include the release of water to a different watershed than the initial water source, which is considered consumption in the methodology used. The HIPS resin average data also includes some plants that release water to a different watershed. Water consumption on-site at the HIPS manufacturing plant makes up 5 percent of the total water consumption for the cradle-to-HIPS system. An additional 9 percent (totaling to 14%) of the total water consumption for the HIPS resin unit process is consumed off-site for producing fuels and electricity used at the HIPS resin plant.

Table 6. Water Consumption for HIPS Resin

	Total Water Consumption		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	Gallons	***Liters***	***%***
Cradle-to-Incoming Materials	665	5,547	86%
Virgin HIPS Resin Production	109	906	14%
Total	**773**	**6,453**	**100%**

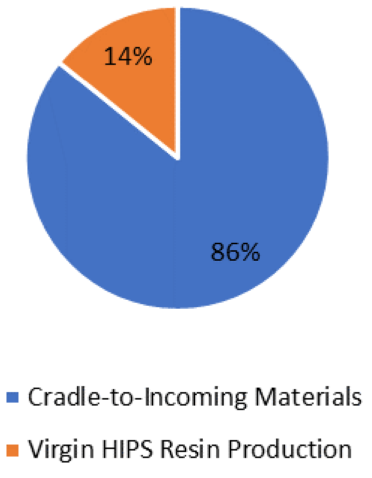

Figure 6. Water Consumption for HIPS Resin

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 hydrochlorofluorocarbons (HCFCs) and chlorofluorocarbons (CFCs), but these contribute less than 0.1 percent of the total shown. Greenhouse gas emissions are mainly from combustion. In the primary data collected for olefins, ethylbenzene/styrene, and HIPS resin, combustion emissions from flare are 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 flares or emission control processes apart 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[13] 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 because feedstock energy is embodied in the resin material, not energy from combustion of the fuel.

In Table 7 and Figure 7, the life cycle GWP results for the HIPS resin system are displayed. Of the total, 94 percent of the GWP are attributed to emissions (both process and fuel-related) associated with production of the incoming materials, including natural gas and petroleum input materials, olefins (ethylene, butadiene and pygas), benzene, ethylbenzene/styrene, mineral oil, and polybutadiene with the remaining emissions (both process and fuel-related) associated with the production of the HIPS resin.

Table 7. Global Warming Potential for HIPS 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	2,722	2,722	94%
Virgin HIPS Resin Production	184	184	6%
Total	**2,906**	**2,906**	**100%**

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

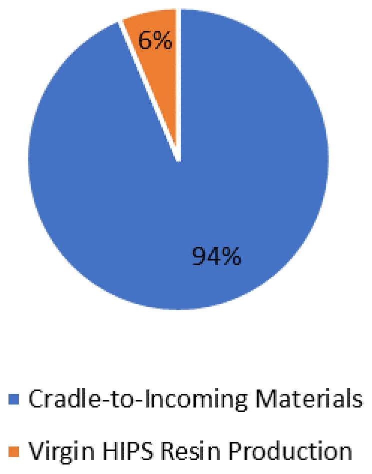

Figure 7. Global Warming Potential for HIPS Resin

Figure 8 displays the GWP separated by process contribution. This figure illustrates the percentages of GWP specific to process emissions at individual unit processes (e.g., benzene production), as well as to fuel-related emissions from the combustion of fuels. Only processes creating at least one percent of the total GWP have been shown individually; all processes making up less than one percent as well as transportation have been grouped into "all other processes."

As shown in Figure 8, the largest amount of the GWP is created by the combustion of natural gas, coal, and oil in both industrial and utility boilers, which accounts for 43 percent of the total GWP. The processing of incoming materials (olefins, ethylbenzene/styrene, and benzene) produces a total of 26 percent of the GWP, which comes directly from the release of greenhouse gases at the plants. A sizable portion of the unit process emissions comes from emission control processes at the plant, such as flares or thermal oxidizers. The natural gas extraction and processing and crude oil extraction/refining used as a material input to the olefins plant creates 16 percent of the total GWP.

Although the GWP from the HIPS resin production is shown as 6 percent of the total in Figure 7, the majority of those emissions are combustion emissions, therefore, part of the 43 percent shown in Figure 8. The process greenhouse gases released at the HIPS resin plants are less than 0.1 percent of the total, due to flaring or emission control processes, which are considered a mix of process and fuel-based emissions.

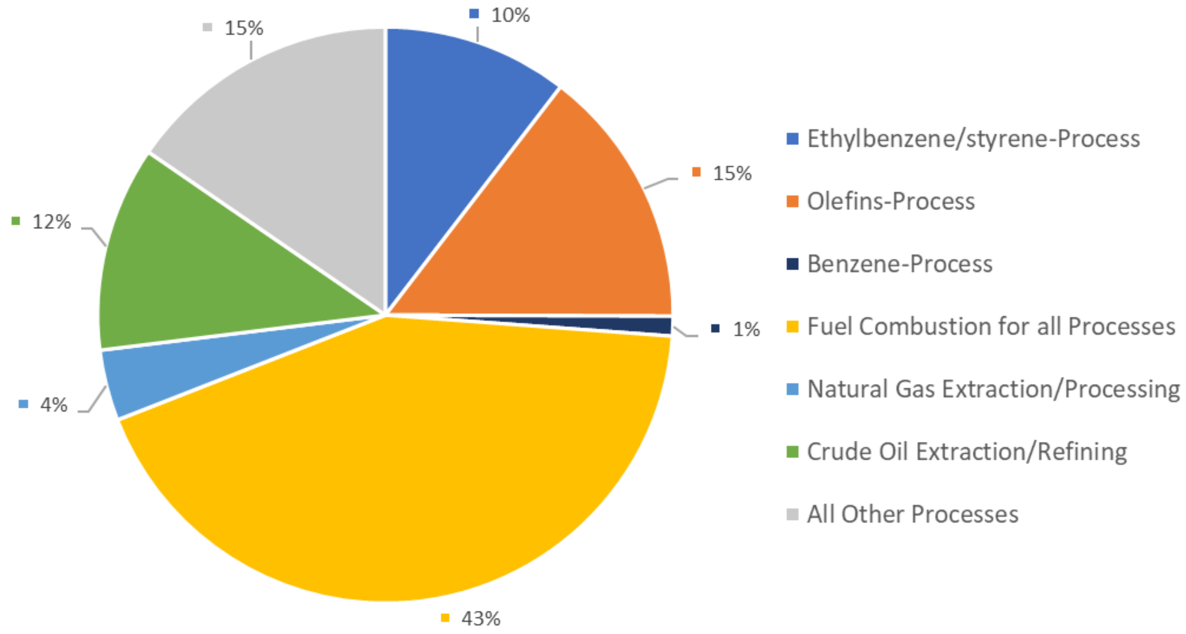

Figure 8. Global Warming Potential by Process Contribution

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.[14,15]

Acidification potential (AP) impacts are typically dominated by fossil fuel combustion emissions or emissions from the extraction and processing of natural gas and oil, particularly sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Oil and gas extraction and processing emissions comprise 48 percent of the total AP, while combustion emissions of all fuels make up 33 percent. Emissions from the combustion of coal to generate grid electricity is the largest single contributor (18 percent) to acidification impacts for the system. Combustion of transportation fuels make up 7 percent of the AP total, while process emissions from benzene contribute 5 percent.

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[14] 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.

[15] 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 8 shows total acidification potential results for the HIPS resin system. Results are shown graphically in Figure 9. In the AP category, 12 percent of the AP is coming from HIPS resin production and about 88 percent comes from the raw and intermediate material unit processes. Only 0.1 percent of the total AP comes directly from the HIPS resin production. Of the 12 percent AP shown in Table 7 for the virgin HIPS resin production, about sixty percent comes from electricity and a third comes from transport.

Table 8. Acidification Potential for HIPS Resin

	Acidification Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb SO2 eq	*kg SO2 eq*	*%*
Cradle-to-Incoming Materials	5.87	5.87	88%
Virgin HIPS Resin Production	0.79	0.79	12%
Total	**6.66**	**6.66**	**100%**

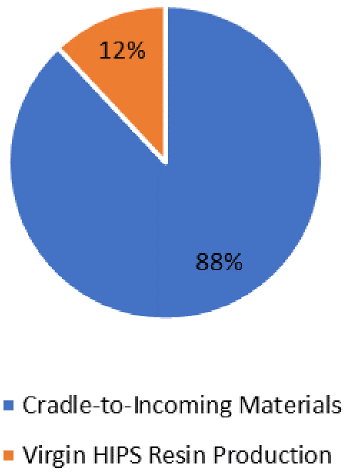

Figure 9. Acidification Potential for HIPS Resin

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.[16] The TRACI characterization factors for

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

eutrophication are the product of a nutrient factor and a transport factor.[17] 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 HIPS resin are shown in Table 9 and illustrated in Figure 10. The largest portion, over 93 percent, of the EP results are associated with the production of the raw and intermediate materials used to create HIPS resin. The extraction and processing/refining of natural gas and oil for materials and fuels releases approximately 49 percent of the emissions related to the EP impact. The various intermediate plant process emissions comprise 24 percent of the EP impact results. The combustion of non-renewable fuels in boilers, equipment and transport creates 16 percent of the emissions characterized as EP. The gate-to-gate HIPS resin production generates 7 percent of the EP impact as seen in Table 9, with half of that percentage representing the combustion of fuels for transport and 35 percent from the electricity use. Only 0.2 percent of the total EP impact comes from process emissions released at the HIPS plant.

Table 9. Eutrophication Potential for HIPS Resin

	Eutrophication Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb N eq	***kg N eq***	***%***
Cradle-to-Incoming Materials	0.35	0.35	93%
Virgin HIPS Resin Production	0.026	0.026	7%
Total	**0.38**	**0.38**	**100%**

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[17] 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.

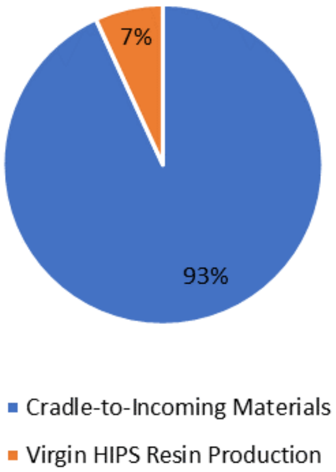

Figure 10. Eutrophication Potential for HIPS Resin

OZONE DEPLETION POTENTIAL

Stratospheric ozone depletion potential (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 HIPS resin system, the main sources of emissions contributing to ODP are minute amounts of a few CFCs, HCFCs, and halons emitted. Some are emitted during the extraction and refining of petroleum, which is used as fuel and material in the production of olefins, benzene and white mineral oil, and some are associated with refrigerants uses.

Table 10 shows total ODP results for the HIPS resin system, which are also shown graphically in Figure 11. Ozone depletion results for the HIPS resin system are dominated by a small amount of refrigerant reported by less than 3 plants, which caused an order of magnitude to be used. This means there is a probability that this amount may be overstated or understated in the average. Discussions with the plants revealed that refrigerant leaks do happen occasionally but are not common yearly. The ODP amount shown in the cradle-to-incoming materials include emissions from crude oil extraction and refining, which contributes 11 percent of the total ozone depletion impacts.

Table 10. Ozone Depletion Potential for HIPS 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	6.5E-06	6.5E-06	11%
Virgin HIPS Resin Production	5.0E-05	5.0E-05	89%
Total	**5.7E-05**	**5.7E-05**	**100%**

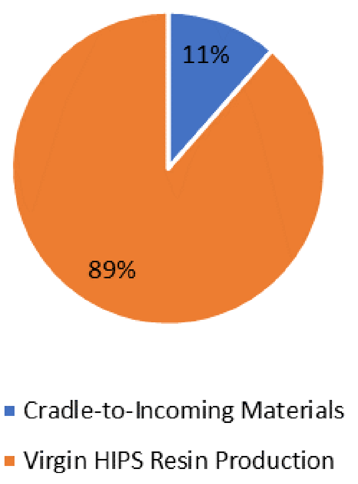

Figure 11. Ozone Depletion Potential for HIPS Resin

PHOTOCHEMICAL SMOG FORMATION

The photochemical ozone creation potential (POCP) impact category, also referred to as smog formation potential, 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. Endpoint effects of such smog creation can include increased human mortality, asthma, and deleterious effects on plant growth.[18] 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. For cradle-to-resin production of HIPS, NO_x makes up 91 percent of the smog formation emissions, with VOCs consisting of almost 9 percent.

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

Smog formation potential results for HIPS resin are displayed in Table 11 and illustrated in Figure 12. Approximately 91% of the POCP impact results are associated with production of the raw and intermediate materials. The polybutadiene, olefins and ethylbenzene/styrene plants release 6 percent of the total emissions resulting the POCP. Almost 60 percent of the total POCP impact results are from the natural gas and oil extraction. The combustion of fuels in boilers, equipment, and for transport release emissions that create 26 percent of the POCP total amount.

The remaining 9 percent of the POCP impact is from HIPS resin production. Of that percentage, half of the POCP amount for the HIPS resin plant comes from the transport of incoming materials. Approximately 35 percent of the POCP is from emissions from generation of electricity used in the plant, which includes the combustion of natural gas and coal at power plants and cogeneration plants. An estimated 0.2 percent of the total emissions resulting in the POCP impact results are released at the HIPS resin plant as process emissions. The remaining percentage in the HIPS resin production comes from combustion of fuels onsite.

Table 11. Photochemical Smog Formation Potential for HIPS 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	152	152	91%
Virgin HIPS Resin Production	14.4	14.4	9%
Total	**167**	**167**	**100%**

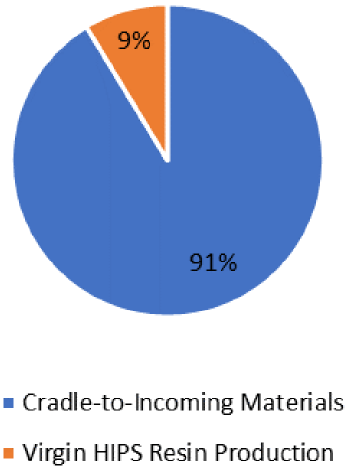

Figure 12. Photochemical Smog Formation Potential for HIPS Resin

COMPARISON OF 2022 AND 2011 LCI AND LCIA HIPS RESULTS

This section provides a comparison of life cycle inventory and impact assessment category results that were included in the original virgin HIPS resin system[19] 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 12 shows the comparable LCI and LCIA categories for the 2011 and 2022 HIPS resin results in both English and SI units and includes the percent change from the 2011 value for each category. Percent change between systems is defined as the difference between the 2022 and 2011 totals divided by the 2011 totals. The results in Table 12 show a decrease in all category totals. 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 the percent change above the comparable bars.

Broadly, results differ between the two averaged datasets predominantly due to the use of different or additional companies and manufacturing plants when updating the olefins, styrene, and HIPS 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, HIPS resin and olefins are representative of the years 2015 and 2016. For olefins, 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. Comparing the HIPS resin plants, four of the five plants that provided data in 2015, also provided data in the original study. One of those plants continues to be owned by the same company, while the other three plants were purchased by another company between 2004 and 2015. Overall, the data collected from those four plants in 2015 and 2016 were similar to their original data in the 2011 report with the exception of a few data points. The original data collection did have six plants, while the current data collection had five plants represented.

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[19] 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.

Table 12. Comparison of 2011 and 2022 LCI and LCIA Results for Virgin HIPS Resin

	1000 pounds of Virgin High-Impact Polystyrene 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***
HIPS 2022	38.1	37.9	0.12	86.9	2,906
HIPS 2011	41.3	41.2	0.17	114	3,259
	1000 kilograms of Virgin High-Impact Polystyrene 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***
HIPS 2022	88.5	88.2	0.28	86.9	2,906
HIPS 2011	96.2	95.8	0.39	114	3,259
Percent Change	8%	8%	29%	24%	11%

*Total Solid Waste excludes hazardous solid waste for 2022 as this category was not included as Solid Waste in 2011.

ENERGY COMPARISON

Overall, the total energy for HIPS resin has decreased 7.7 GJ on a 1,000 kg basis (3.2 million (MM)Btu/1,000 lb). There is an 8 percent decrease in total energy as compared to the original study's results. When comparing the HIPS resin unit process averaged energy data, data from the plants collected for both studies had minor changes, such as the electricity amounts increasing by small amounts, while other fuels decreased by small amounts. The natural gas used onsite in boilers did decrease, which possibly is due to the use of byproducts available as fuels at the plant. Certainly, the use of different plants for some intermediate steps affected the change in energy**.** Figure 13 provides a graphical perspective of the unit processes associated with this energy decrease from the original energy amounts.

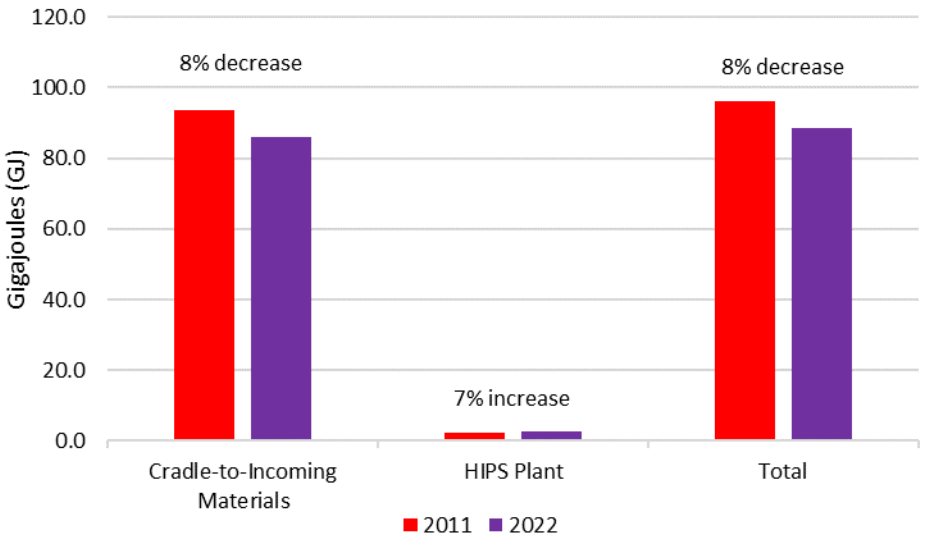

Figure 13. Change in Energy by Stage per 1,000 kg (GJ)

The energy of material resource, which pertains to the amount of inherent energy from the raw materials increased by a small amount for HIPS resin due to the changes in the amount of raw material inputs on 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 by a greater percentage than the 8 percent shown in the total. As the styrene updated data remained similar to its previous data, it can also be concluded that this decrease is due to the energy decreases in the energy requirements for the olefins plants (ethylene, pyrolysis gasoline, and butadiene), as well as the oil and natural gas extraction and processing/refining. The energy for converting the raw materials to HIPS resin increased by 7 percent compared to the 2004-2006 energy for this process. This does not mean that efficiency has not improved, since there was a difference in plants participating in the current and original analyses. The fact that the current average energy usage is remarkably 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 renewable energy decreased about 29 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 many of the raw material and intermediate processes required to manufacture HIPS 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 HIPS.

SOLID WASTE COMPARISON

When compared to the 2011 HIPS resin total solid waste amount, the current HIPS resin study shows 27 kg per 1000 kg HIPS resin less solid waste, which is a 24 percent decrease from the original study. Much of this decrease is due to the differences in primary data and updated secondary raw material data collected between the 2011 and 2022 reports. Figure 14 provides a visual of the total solid waste amount split out by the HIPS unit process and cradle-to-incoming materials. A decrease occurs for both cradle-to-incoming materials and at the HIPS plant. Comparing the current process solid waste at the HIPS plant to the 2011 solid waste, a decrease is seen both in process solid waste and solid waste created by fuel use at the plants. Although the energy amount specific to the HIPS plant increased, the types of fuels used for electricity have changed. This decrease is partially due to the decrease in coal use in the electricity grid used in 2016 as compared to the previous grid used. The average process solid waste, which is created on-site, has decreased from the 2011 amount by almost 70 percent. The decrease in cradle-to-incoming-materials is a mix of lower amounts of solid waste at the plants, as well as an overall decrease in the electricity use of the olefins plant. Process solid wastes from the natural gas and crude oil production also decreased by small amounts.

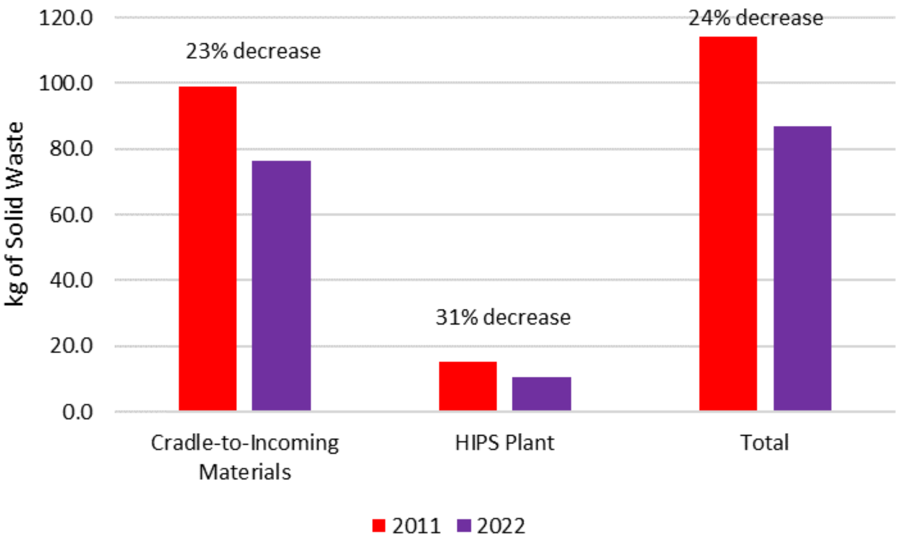

Figure 14. Change in Solid Waste Weight by Unit Process (kg Per 1,000 kg)

GLOBAL WARMING POTENTIAL COMPARISON

The total global warming potential decreased by 353 kg CO_2 equivalents (eq)/1000 kg HIPS resin, an approximate 11 percent decrease. Figure 15 displays a column chart with the HIPS resin and cradle-to-incoming materials results that makeup the decrease when comparing the 2011 and 2022 GWP results. 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.

The GWP specific to the HIPS resin plant increased by 20 percent, while the energy for the plant also increased, although by a lower percentage. The larger increase in GWP compared to energy is mainly due to reported carbon dioxide amounts included from flares/thermal oxidizers as process emissions, which were not separated from fuel combustion in the previous average dataset. These small amounts of greenhouse gases from flares/thermal oxidizers could potentially be double counted as part of the calculated fuel combustion emissions but have been incorporated to assure CO_2 from any process emissions being flared/oxidized are included. Because the HIPS plant GWP amount is only 6 percent of the total GWP amount, this increase is small enough that it can be considered as equivalent to the previous amounts. The decrease in GWP for the cradle-to-incoming materials 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.

It should also be noted that the characterization factors for the GWP have changed since the 2011 report. The methane amount increased from 25 to 28 lb CO_2eq/1 lb methane and the nitrous oxide amount decreased from 298 to 265 lb CO_2eq/1 lb. As the methane and nitrous oxide releases account for less than 10 percent of the GWP characterization, the change in results due to this characterization factor difference is small.

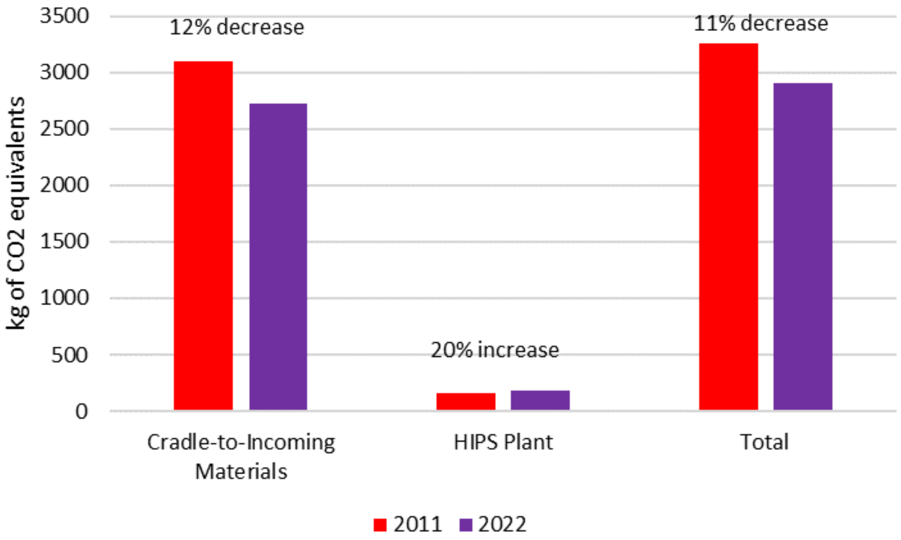

Figure 15. Change in Global Warming Potential by Unit Process (kg of CO2 eq. per 1,000 kg)

APPENDIX: HIGH IMPACT POLYSTYRENE (HIPS) MANUFACTURE

This appendix discusses the manufacture of high impact polystyrene (HIPS) resin. HIPS is used to make thermoformed, injection molded and extruded products, packaging for food, appliances parts, and consumer electronics. Approximately 1,836 million pounds of HIPS was produced in the U.S. and Canada in 2015 (ACC, 2016). The material flow for HIPS resin is shown in Figure 16.

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:

- Benzene Production
- Ethylbenzene/Styrene Production
- White Mineral Oil Production
- Polybutadiene Production
- High impact polystyrene resin production

LCI data for olefins (ethylene, pyrolysis gasoline, and butadiene), ethylbenzene/styrene, and HIPS production were collected for this update to the U.S. LCI plastics database by member companies of the American Chemistry Council. Benzene plant data was not updated from the original 2011 resins report; however, the unit processes for the input materials were updated. Updated secondary data was used for crude oil extraction and refining and natural gas production and processing, and white mineral oil production. Results and LCI data for the production of olefins (ethylene, pygas, and butadiene), oil, and natural gas can be found in the report, ***Cradle-to-Gate Life Cycle Analysis of Olefins***[20]. Butadiene results are available in the aforementioned report with limited detail in some LCI categories. Butadiene's unit process data was not included in this report due to limited data providers. The LCI data for butadiene is considered confidential and therefore is not shown.

BENZENE PRODUCTION

Benzene is the most widely used aromatic petrochemical raw material. The two major sources of benzene are catalytic reformate and pyrolysis gasoline (Kent, 2003). Additional benzene is produced by the toluene disproportionate processes but is not included in this analysis. (Meng et al., 2021).

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

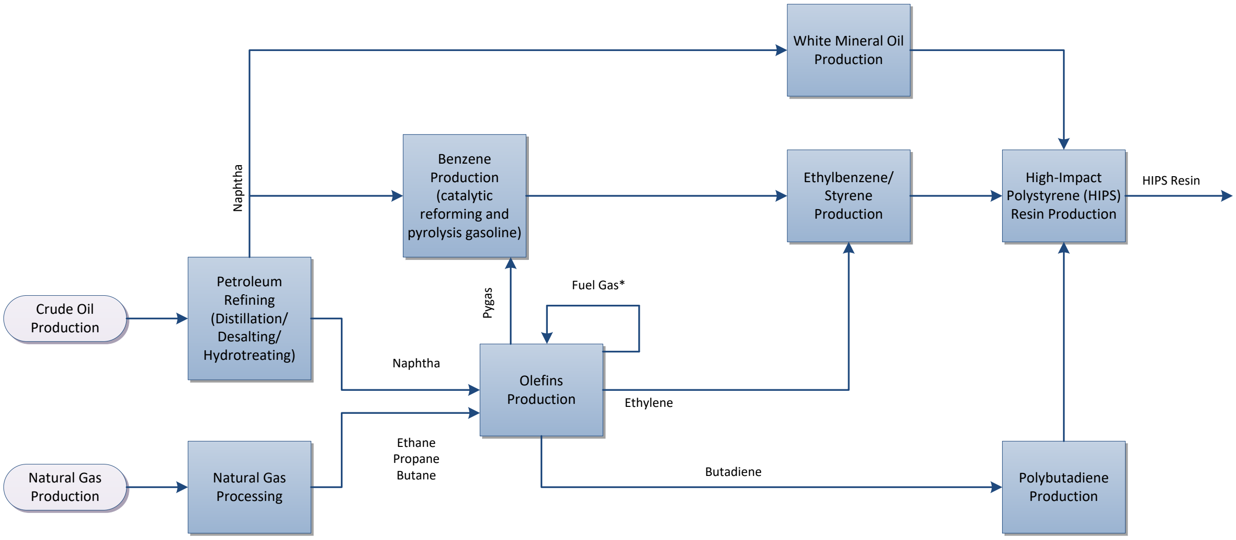

Figure 16. Flow diagram for the Production of High impact polystyrene (HIPS) Resin.
* Fuel gas used for energy is created from off-gas produced in the process.

In the reforming process, naphtha is fed through a catalyst bed at elevated temperatures and pressures. The most common type of reforming process is platforming, in which a platinum-containing catalyst is used. Products obtained from the platforming process include aromatic compounds (benzene, toluene, xylene), hydrogen, light gas, and liquefied petroleum gas. The aromatics content of the reformate varies and is normally less than 60 percent (Gentry, 2007). The reformate from the platforming process undergoes solvent extraction and fractional distillation to produce pure benzene, toluene, and other coproducts.

Pyrolysis gasoline is a byproduct of the steam cracking of hydrocarbons for the production of ethylene and propylene. Raw pyrolysis gas is composed of a mixture of C_5 to C_8 hydrocarbons, including several aromatic compounds. To separate the aromatics from the resulting mixture, a very polar solvent (commonly an alcohol) is used to dissolve the aromatic components. The aromatics can then be separated from the solvent using fractional distillation. The solvent is recovered and re-used.

Table 13 represents the energy requirements and environmental emissions for producing benzene. Only catalytic reforming and pyrolysis gasoline are considered as the source of benzene in this analysis. These sources account for 70 percent of the world production of benzene (Niziolek, et. al., 2016). It is estimated that one-third of this production is from pyrolysis gasoline and two-thirds are produced from catalytic reforming. The collected datasets were weighted using these fractions.

Table 13. LCI Data for the Production of Benzene

	1,000 lb	1,000 kg
Material Inputs		
Refined Petroleum Products- material use	667 lb	667 kg
Refined Petroleum Products- fuel use	16 lb	16 kg
Processesed Natural Gas - fuel use	22.1 lb	22 kg
Pygas	335 lb	335 kg
Energy		
Process Energy		
Electricity from grid	7.26 kWh	16.0 kWh
Electricity from cogen	4.35 kWh	9.60 kWh
Natural gas	625 ft^3	39.0 m^3
Residual fuel oil	3.83 gal	32.0 l
Distillate fuel oil	0.40 gal	3.30 l
Transportation Energy		
Barge		
Diesel	11.5 ton·mi	37.0 tonne·km
Residual oil	37.3 ton·mi	120 tonne·km
Rail	46.6 ton·mi	150 tonne·km
Pipeline - petroleum products	74.6 ton·mi	240 tonne·km
Truck	9.32 ton·mi	30.0 tonne·km
Environmental Emissions		
Atmospheric Emissions		
Carbon monoxide	45.0 lb	45.0 kg
Carbon dioxide, fossil	1.0E-04 lb	1.0E-04 kg
Chlorine	0.062 lb	0.062 kg
Nitrogen oxides	0.019 lb	0.019 kg
Particulates, > 2.5 um, and < 10um	0.010 lb	0.010 kg
NMVOC, non-methane volatile organic compounds, unspecified origin	1.0E-06 lb	1.0E-06 kg
Hydrogen	0.44 lb	0.44 kg
Sulfur oxides	0 lb	0 kg
Waterborne Releases		
Benzene	1.0E-06 lb	1.0E-06 kg
BOD5, Biological Oxygen Demand	0.47 lb	0.47 kg
COD, Chemical Oxygen Demand	1.10 lb	1.10 kg
Suspended solids, unspecified	0.11 lb	0.11 kg
Oils, unspecified	0.018 lb	0.018 kg
Sulfide	0.0010 lb	0.0010 kg
Suspended solids, unspecified	0.0010 lb	0.0010 kg
TOC, Total Organic Carbon	1.0E-05 lb	1.0E-05 kg
Solid Wastes		
Solid waste, process to landfill	0.43 lb	0.43 kg
Solid waste process, to incineration	0.051 lb	0.051 kg
Water Consumption	0.75 gal	6.30 l

Source: Primary Data, 2003; Primary Data, 1992

Numerous aromatic coproduct streams are produced during this process. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel use. When these fuel coproducts are exported from the aromatics separation process, they carry with them the mass allocated share of the inputs and outputs for their production, which is discussed in the methodology section.

No energy credit is applied for the exported fuels, since both the inputs and outputs for the exported fuels have been removed from the data set. Table 13 shows the averaged energy and emissions data for the production of benzene.

There are several benzene producers and production plants in the U.S. as the chemical is ranked in the top 20 chemicals for production volume. (CDC, 2018) The benzene data collected for the benzene from pygas in this module represent one producer and one plant in the U.S from 2003. While data was collected from a small sample of plants, the benzene producer who provided data for this module verified that the characteristics of their plant are representative of the extraction of benzene from pyrolysis gasoline for North American benzene production. The average dataset of the three plants for both types of benzene production was reviewed and accepted by the benzene data provider.

The primary data used for the catalytic reformation process was collected for 1992. This data represented two plants from two companies. Although there have certainly been some updates made to the process, research into this process found no major changes to the process. It should be noted that benzene may be somewhat overstated in the results.

One of the three datasets used was collected and represents 2003 data, while the other two datasets are from 1992. The 2003 data were collected from direct measurements and engineering estimates. The collection methods for the 1992 data are not specified.

ETHYLBENZENE/STYRENE PRODUCTION

The production of styrene monomer is accomplished through a series of processes. The first is the production of ethylbenzene by the alkylation of benzene with ethylene. In this process, benzene initially passes through a drying column. From the drying column, the benzene and ethylene are mixed in a reactor with a suitable catalyst. This reaction is exothermic and occurs at relatively low pressures and temperatures. Unreacted benzene is removed and recycled back to the process. The ethylbenzene is then separated from the solution. The heavy bottoms, tars, and vent gases are burned while the solution is recycled back to the reactor.

Styrene is produced by dehydrogenation of ethylbenzene. The ethylbenzene is mixed with steam, then allowed to come in contact with a catalyst in a reactor. This reaction is conducted at high temperature under vacuum. The heat is recovered from this reaction, and the hydrocarbon solution is sent to a series of fractionation units. The first separation removes the small amount (4 to 6 percent) of toluene and benzene produced by cracking. This toluene/benzene stream is typically sent back to the benzene plant. The second separation removes unreacted ethylbenzene and recycles it back into the system. Purified styrene monomer is recovered in the third and final phase. Bottoms or tar residue is removed from this third phase (Hydrocarbon Processing, 1997).

Table 14 displays the energy requirements and environmental emissions for the production of styrene including the production of ethylbenzene. Two of the three ethylbenzene/styrene datasets were collected for the original ACC resin project and represents 2002-2003 data, while the other dataset was collected for 2015 for this project. All datasets were collected from direct measurements, purchasing/utility records, and engineering estimates. Toluene or a benzene/toluene mix are produced as coproduct streams during this process. A mass allocation was used to partition the credit for these coproducts.

As of 2017, the U.S. produced 4,302 million pounds of polystyrene (PIPS, 2018). The styrene data collected for this module represent three producers and three plants in the U.S. Only one of these datasets was collected from the 2015 timeframe. The other two datasets were from the original resin database in 2002-2003. The 2015 data was compared to the 2002-2003 data and the differences between the dataset were considered not significantly different statistically. While data was collected from a small sample of plants, the styrene producers who provided data for this module verified that the characteristics of their plants are representative of North American styrene production. The average dataset was reviewed and accepted by the styrene data provider from 2015.

Table 14. LCI Data for the Production of Ethylbenzene/Styrene

	1,000 lb		1,000 kg		
Material Inputs					
Ethylene	288	lb	288	kg	
Benzene	781	lb	781	kg	
Energy					
Process Energy					
Electricity from grid	75.2	kWh	165.7	kWh	
Natural gas	6,423	ft^3	401	m^3	
Transportation Energy					
Pipeline -refinery products	5.1	ton·mi	16.5	tonne·km	
Barge	4.0	ton·mi	13.0	tonne·km	
Environmental Emissions					
Atmospheric Emissions					
Carbon monoxide	0.33	lb	0.33	kg	
Carbon dioxide, fossil	330	lb	330	kg	
Nitrogen oxides	0.1	lb	0.1	kg	*
Sulfur oxides	1.00E-04	lb	1.0E-04	kg	*
VOC, volatile organic compounds	0.001	lb	0.001	kg	*
Particulates, > 2.5 um, and < 10um	0.001	lb	0.001	kg	*
Particulates, unspecified	0.001	lb	0.001	kg	*
Particulates, < 10 um	0.01	lb	0.01	kg	*
Methane	0.001	lb	0.001	kg	*
Nitrous oxide	1.0E-04	lb	1.0E-04	kg	*
Waterborne Releases					
Benzene, ethyl-	0.001	lb	0.001	kg	*
Styrene	0.001	lb	0.001	kg	*
Suspended solids, unspecified	0.001	lb	0.001	kg	*
BOD5, Biological Oxygen Demand	0.001	lb	0.001	kg	*
Phosphorous acid	1.0E-06	lb	1.00E-06	kg	*
Solid Wastes					
Solid waste, process to landfill	0.001	lb	0.001	kg	
Solid waste process, to incineration	1.00E-04	lb	1.00E-04	kg	
Hazardous waste to landfill	1.00E-05	lb	1.00E-05	kg	
Water Consumption	0.99	gal	8.3	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, 2015; Primary Data, 2002-2003

MINERAL OIL PRODUCTION

Mineral oils are mixtures of highly refined paraffinic and naphthenic liquid hydrocarbons and have boiling points greater than 200° Celsius (Vavasour and Chen, 2005). The initial distillation of crude oil is used to remove lighter petroleum fractions, such as gasoline and naphtha, and the remaining fractions consist of raw materials for fuel oil, coke, lubrication grease, and asphalts. This residue is processed through a vacuum distillation column to isolate the raw materials for lubricating oil production.

Lubricating oil production includes hydrotreating, deasphalting, and dewaxing processes that eliminate components such as multiple-ring aromatics, asphalt-like compounds, and straight-chain paraffins. The extensive refining requirements for mineral oil production result in high energy requirements in comparison to other refinery products. However, mineral oil (and other components of the lubricating oil category) represent less than one percent of total refinery output; thus, while they are energy intensive, they represent a small share of total refinery energy.

Mineral oil is used in plastics, such as polystyrene, to improve and control the melt flow rate of the finished polymer (Vavasour and Chen, 2005). Additionally, white mineral oil is added to the finished polymer to prevent adherence to a mold and improve other physical characteristics. The energy and environmental emissions shown in Table 15 relate to the production of mineral oil.

Table 15. LCI Data for the Production of White Mineral Oil

	1,000 lb		1,000 kg	
Material Inputs				
Refined Petroleum Products	1,000	lb	1,000	kg
Energy				
Process Energy				
Electricity from grid	186	kWh	410	kWh
Natural gas	1201	ft^3	75	m^3
Residual fuel oil	21.6	gal	180	l
Liquid petroleum gas (LPG)	0.93	gal	7.8	l
Transportation Energy				
Pipeline -refinery products	106	ton·mi	340	tonne·km
Truck	13.7	ton·mi	44	tonne·km
Rail	8.7	ton·mi	28	tonne·km
Environmental Emissions				
Atmospheric Emissions				
Methyl ethyl ketone	0.10	lb	0.10	kg
VOC, volatile organic compounds	0.10	lb	0.10	kg
Waterborne Releases				
Chromium	0.001	lb	0.001	kg
Chromium VI	8.7E-05	lb	8.70E-05	kg
Phenols, unspecified	9.0E-04	lb	9.00E-04	kg

Source: Vavasour and Chen, 2005

POLYBUTADIENE PRODUCTION

Polybutadiene is the second largest synthetic rubber produced in volume. Polybutadiene has two main uses, the first being tire production which accounts for 70% of polybutadiene production and the second is the fortification of plastics which makes up approximately 25% of total production. (Valentini and Manchado, 2020).

The production of polybutadiene may be accomplished by different pathways depending on the source of butadiene. One pathway to achieve the production of polybutadiene is through dehydrogenation of n-butane or mixture of n-butane and butenes followed by purification of butadiene and polymerization into polybutadiene (Jenkins, 2019).

The removal of hydrogen from butanes/butenes is accomplished by heating and passing through reactors containing catalysts to produce butadiene. Typical solution polymerization of butadiene includes the use of Ziegler-Natta catalysts. Catalysts comprised of transition metals and lanthanides with alternative alkylating agents such as methylaluminoxane (MAO) have been used for the past 20 years (Ricci, 2014). Butadiene is purified by passing through several distillation columns to remove polymeric compounds and followed by extraction with an organic solvent such as N-Methyl-2-pyrrolidone (NMP). After purification, high quality butadiene is treated to remove inhibitors, mixed with a solvent and passed through multiple continuously stirred reactors to polymerize into polybutadiene. The solvent is removed from the polybutadiene solution and recovered using a stripper. Finally, the polybutadiene product is dried and baled for storage.

The energy requirements and environmental emissions for the production of polybutadiene are shown in Table 16. No data was collected for this process. The energy data comes from a 1970s source, which was reviewed by a polybutadiene producer for the original resins study. Transportation data was estimated, and emissions data come from secondary source from the 1990s.

Table 16. LCI Data for the Production of Polybutadiene

	1,000 lb	1,000 kg
Material Inputs		
Butadiene	1,003 lb	1,003 kg
Energy		
Process Energy		
Natural gas	2323 ft^3	145 m^3
Transportation Energy		
Pipeline -refinery products	45.7 ton·mi	147 tonne·km
Truck	96.3 ton·mi	310 tonne·km
Rail	96.3 ton·mi	310 tonne·km
Environmental Emissions		
Atmospheric Emissions		
Butadiene	3.07 lb	3.07 kg
Waterborne Releases		
Butadiene	0.12 lb	0.12 kg

Source: MRI 1974, Franklin Associates 2021, Mullins 1990 and EPA 1996.

HIGH IMPACT POLYSTYRENE (HIPS) PRODUCTION

High impact polystyrene (HIPS) is produced by dispensing styrene in water in a reactor and polymerizing in the presence of initiators and suspending agents. Mass polymerization is the most common polymerization process for HIPS in the United States. Various types of continuous reactors are used for this process (Primary data, 2015-2016).

Mass polymerization, also known as bulk polymerization, is one of the simplest methods of polymerization. It is often used in the polymerization of step-growth polymers. During step-growth polymerization, the functional sites of monomers react, liberate a small molecule such as water, and repeat the reaction to produce longer and longer polymer chains. Mass polymerization does not suspend the reactants in a solution such as water or organic solvents. Since water or organic solvents are not used, there is a lower chance for contamination of the product (Kent, 2003).

The process begins with the styrene monomer fed along with processing aids into a reactor. Other chemicals can be added, such as chain transfer agents or anti-oxidants, but these are normally below the one percent threshold for inclusion. Ethylbenzene or toluene may also be added in small amounts to control the polymerization rate. The polybutadiene is shredded and melted into a suspension with styrene monomer. In the reactor, the styrene is grafted onto the polybutadiene. The polystyrene reaction gives off heat as polystyrene solids are formed, which is used to heat the feed with the excess removed from the process. Tower reactors are then used to achieve high polystyrene conversion. Following discharge from tower reactors, the polystyrene stream is devolatilized, which separates out the polymer from the remaining monomer with solvent. This stream is recycled back into the reactor at regular intervals. The polymer is extruded into pellets for transport to fabricators.

An individual weighted average for four leading HIPS resin producers (five plants) in the United States was calculated using the production amounts from each plant for HIPS resin. 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 HIPS resin production amount is approximately 62 percent of the HIPS resin production in the U.S. in 2015 (ACC, 2016). Only small amounts of off-spec product are coproducts of HIPS resin production, and a mass basis was used to allocate the environmental burdens among the coproducts.

HIPS resin producers from the United States provided data from their facilities using technology ranging from average to state-of-the-art. Most of the producers use mass polymerization in continuous reactors, while others stated confidential processes with less detail provided.

Primary data were collected from HIPS manufacturers from the year 2015 (four plants) and 2016 (one plant). 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 HIPS production in North America.

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

Table 17 shows the averaged energy and emissions data for the production of 1,000 pounds and 1,000 kilograms of HIPS resin. In the case of some emissions, data was provided by fewer than the three 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 17. LCI Data for the Production of High Impact Polystyrene (HIPS)

	1,000 lb		1,000 kg		
Material Inputs					
Ethylbenzene styrene	920	lb	920	kg	
Polybutadiene	82.0	lb	82.0	kg	
White mineral oil	16.0	lb	16.0	kg	
Energy					
Process Energy					
Electricity from grid	63.5	kWh	140	kWh	
Natural gas	288	ft^3	18.0	m^3	
Gasoline	7.1E-04	gal	5.9E-06	m^3	
Diesel	1.1E-03	gal	9.5E-06	m^3	
Liquid petroleum gas (LPG)	8.0E-04	gal	6.7E-06	m^3	
Transportation Energy					
Truck	31.1	ton·mi	100	tonne·km	
Rail	43.5	ton·mi	140	tonne·km	
Barge	155	ton·mi	500	tonne·km	
Pipeline -refinery products	0.47	ton·mi	1.5	tonne·km	
Ocean freighter	13.4	ton·mi	43.0	tonne·km	
Environmental Emissions					
Atmospheric Emissions					
Particulates, unspecified	0.044	lb	0.044	kg	*
Particulates, < 2.5 um	0.010	lb	0.010	kg	*
Particulates, > 2.5 um, and < 10um	0.010	lb	0.010	kg	*
Nitrogen oxides	0.011	lb	0.011	kg	
Sulfur oxides	1.0E-04	lb	1.0E-04	kg	*
Carbon dioxide	21.0	lb	21.0	kg	
Methane	1.2E-04	lb	1.2E-04	kg	
Nitrous oxide	4.6E-03	lb	4.6E-03	kg	
Methane, chlorodifluoro-, HCFC-22	1.0E-03	lb	1.0E-03	kg	*
Carbon monoxide	0.01	lb	0.01	kg	*
Aldehydes, unspecified	1.0E-05	lb	1.0E-05	kg	*
Ammonia	1.0E-04	lb	1.0E-04	kg	*
Chlorine	1.0E-05	lb	1.0E-05	kg	*
Styrene	0.02	lb	0.02	kg	
Benzene, ethyl-	3.5E-03	lb	3.5E-03	kg	
Benzene	1.0E-05	lb	1.0E-05	kg	*
Cumene	1.0E-05	lb	1.0E-05	kg	*
N-propylbenzene	1.0E-05	lb	1.0E-05	kg	*
Toluene	1.0E-03	lb	1.0E-03	kg	*
Xylene	1.0E-04	lb	1.0E-04	kg	*
Terphenyl	1.0E-03	lb	1.0E-03	kg	*

Table 17. LCI Data for the Production of High Impact Polystyrene (HIPS) (Continued)

Waterborne Releases					
Dissolved solids					
BOD5, Biological Oxygen Demand	1.0E-05	lb	1.0E-05	kg	*
COD, Chemical Oxygen Demand	1.0E-06	lb	1.0E-06	kg	*
Phenol	1.0E-06	lb	1.0E-06	kg	*
Oils, unspecified	1.0E-07	lb	1.0E-07	kg	*
Suspended solids, unspecified	1.0E-06	lb	1.0E-06	kg	*
Cyanide	1.0E-06	lb	1.0E-06	kg	*
Chromium	1.0E-09	lb	1.0E-09	kg	*
Iron	1.0E-10	lb	1.0E-10	kg	*
Aluminum, ion	1.0E-09	lb	1.0E-09	kg	*
Nickel	1.0E-08	lb	1.0E-08	kg	*
Lead	1.0E-09	lb	1.0E-09	kg	*
Phosphate	1.0E-09	lb	1.0E-09	kg	*
Zinc	1.0E-09	lb	1.0E-09	kg	
Ammonia	4.9E-06	lb	4.9E-06	kg	*
TOC, Total Organic Carbon	1.0E-08	lb	1.0E-08	kg	*
Styrene	1.0E-06	lb	1.0E-06	kg	*
Benzene, ethyl-	1.0E-07	lb	1.0E-07	kg	*
Toluene	1.0E-08	lb	1.0E-08	kg	*
Phosphorus	1.0E-09	lb	1.0E-09	kg	*
Solid Wastes					
Solid waste, process to landfill	0.76	lb	0.76	kg	
Solid waste sold for recycling or reuse	0.010	lb	0.010	kg	
Non-hazardous waste to WTE	0.59	lb	0.59	kg	
Hazardous waste to incineration	0.079	lb	0.079	kg	
Hazardous waste to WTE	0.380	lb	0.380	kg	
Water Consumption	38.3	gal	320	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, 2015-2016

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