CRADLE-TO-GATE LIFE CYCLE ANALYSIS OF ACRYLONITRILE BUTADIENE STYRENE (ABS) RESIN

Final Report

Submitted to:

American Chemistry Council (ACC) Plastics Division

Submitted by:

Franklin Associates, A Division of ERG

November, 2022

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PREFACE

This life cycle assessment of acrylonitrile butadiene styrene (ABS) 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. 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 ABS resin.

This report was prepared for ACC by Franklin Associates, A Division of Eastern Research Group, Inc. as an independent contractor. This project was managed by Melissa Huff, Senior LCA Analyst and Project Manager, who was also lead for modeling and report writing. Anne Marie Molen assisted with data collection tasks and report/appendix preparation. Paige Weiler and Ben Young assisted with research.

Franklin Associates gratefully acknowledges the significant contribution to this project by Allison Chertack, Prapti Muhuri, Mike Levy (First Environment, formerly ACC), and Keith Christman of ACC in leading this project. Also acknowledged are the following companies: INEOS Styrolution, SABIC, and Trinseo who graciously provided primary Life Cycle Inventory data for ABS 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.

November, 2022

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LIST OF ACRONYMS

(Alphabetical)

ABS	ACRYLONITRILE BUTADINE STYRENE
ACC	AMERICAN CHEMISTRY COUNCIL
AP	ACIDIFICATION POTENTIAL
API	AMERICAN PETROLEUM INSTITUTE
BOD	BIOCHEMICAL OXYGEN DEMAND
COD	CHEMICAL OXYGEN DEMAND
CFC	CHLOROFLUOROCARBON
EGRID	EMISSIONS & GENERATION RESOURCE INTEGRATED DATABASE
EIA	ENERGY INFORMATION ADMINISTRATION
EP	EUTROPHICATION POTENTIAL
ERG	EASTERN RESEARCH GROUP, INC
EQ	EQUIVALENTS
GHG	GREENHOUSE GAS
GHGRP	GREENHOUSE GAS REPORTING PROGRAM
GJ	GIGAJOULE
GREET	GREENHOUSE GASES, REGULATED EMISSIONS, AND ENERGY USE IN TECHNOLOGIES
GWP	GLOBAL WARMING POTENTIAL
HCFC	HYDROCHLOROFLUOROCARBON
HGR	HIGH GRAFT RUBBER
IPCC	INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
ISO	INTERNATIONAL ORGANIZATION FOR STANDARDIZATION
LCA	LIFE CYCLE ASSESSMENT
LCI	LIFE CYCLE INVENTORY
LCIA	LIFE CYCLE IMPACT ASSESSMENT
LPG	LIQUEFIED PETROLEUM GAS
MJ	MEGAJOULE

MM	MILLION
NAICS	NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM
NAPAP	NATIONAL ACID PRECIPITATION ASSESSMENT PROGRAM
NGL	NATURAL GAS LIQUID
NMVOC	NON-METHANE VOLATILE ORGANIC COMPOUNDS
NREL	NATIONAL RENEWABLE ENERGY LABORATORY
ODP	OZONE DEPLETION POTENTIAL
POCP	PHOTOCHEMICAL SMOG FORMATION (HISTORICALLY PHOTOCHEMICAL OXIDANT CREATION POTENTIAL)
RCRA	RESOURCE CONSERVATION AND RECOVERY ACT
SI	INTERNATIONAL SYSTEM OF UNITS
TRACI	TOOL FOR THE REDUCTION AND ASSESSMENT OF CHEMICAL AND OTHER ENVIRONMENTAL IMPACTS
TRI	TOXIC RELEASE INVENTORY

CRADLE-TO-GATE LIFE CYCLE ASSESSMENT OF ACRYLONITRILE BUTADIENE STYRENE (ABS) 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 acrylonitrile butadiene styrene (ABS) resin, which is used in a variety of end use applications including automotive applications, appliance parts, electrical and electronics applications and pipes/fittings. 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.

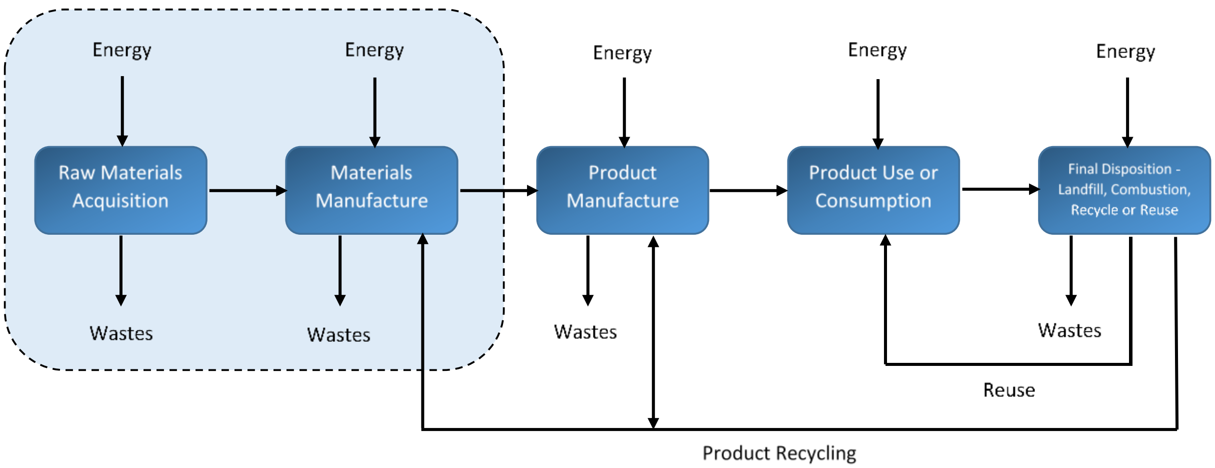

Figure 1. General materials flow for "cradle-to-grave" analysis of a product system. The dashed box indicates the boundaries of this analysis.

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 ABS resin. It is considered a cradle-to-gate boundary system because this analysis ends with the ABS resin production. The system boundaries stop at the ABS 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 appliance, automotive and electronics parts. 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) 14040:2006 and 14044:2006 standard documents[1].

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

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

The LCI identifies and quantifies the material inputs, energy consumption, water consumption, and environmental emissions (atmospheric emissions, waterborne wastes, and solid wastes) over the defined scope of the study. The LCI data for the polybutadiene and ABS unit processes are shown separately in the attached Appendix. Although data was collected for acrylonitrile for a previous update of this study, LCI data are not shown to protect confidentiality of the producer. The LCI data for the olefins system is shown in the appendix of a separate report, ***Cradle-to-Gate Life Cycle Analysis of Olefins, Final Report*[2].** LCI data for the production of benzene and ethylbenzene/styrene are found in the report, ***Cradle-to-Gate Life Cycle Analysis of General-Purpose Polystyrene, Final Report*[3]**. LCI data for the production of ammonia are found in the report, ***Cradle-to-Gate Life Cycle Analysis of Methylene Diphenyl Diisocyanate (MDI), Final Report*[4]**. All unit processes will be made available to the National Renewable Energy Laboratory (NREL) who maintains the U.S. LCI Database.

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

[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, Final Report. Franklin Associates. Submitted to the Plastics Division of the American Chemistry Council. April, 2020.

[3] Cradle-to-Gate Life Cycle Analysis of General-Purpose Polystyrene, Final Report. Franklin Associates. Submitted to the Plastics Division of the American Chemistry Council. February, 2022.

[4] Cradle-to-Gate Life Cycle Analysis of Olefins, Final Report. Franklin Associates. Submitted to the Plastics Division of the American Chemistry Council. July, 2022

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.

STUDY GOAL AND INTENDED USE

The purpose of this LCA is to document the LCI data and then evaluate the environmental profile of ABS 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 ABS resin and
- To provide information about the environmental burdens associated with the production of ABS resin. The LCA results for ABS production can be used as a benchmark for evaluating future updated ABS results for North America.

According to ISO 14040 and 14044 standards, a peer review of this Cradle-to-Gate LCA of ABS resin report 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 ABS resin is its forming into various products, for example, various components for the electrical or automotive industries. As the study boundary concludes at the ABS 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 ABS 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 ABS resin manufacture:

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

Because upstream olefin manufacture impacts the results for the production of ethylbenzene used to produce ABS, discussion of ethylene 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, Final Report*[2]**.** This report presents LCI results, as well as LCIA results, for ABS resin manufacture. Figure 2 presents the flow diagram for the production of ABS resin. A unit process description and tables for each box shown in the flow diagram can be found in the attached appendix or in a previously released report.

Technological Scope

The manufacture of ABS resin is accomplished by combining three monomers; butadiene acrylonitrile, and styrene The two standard technologies for ABS production in North America are emulsion or mass polymerization. Both technologies are represented within the production dataset. Emulsion technology begins with the polymerization of butadiene in water followed by polymerization of acrylonitrile and styrene in the rubber latex solution and grafting onto the polybutadiene latex elastomer substrate. Mass polymerization technology is a continuous process in which styrene and acrylonitrile are polymerized in the presence of a rubber substrate such as polybutadiene.

The data collection methods for ABS include direct measurements, information provided by direct measurement, purchasing and utility records, calculations from equipment specifications, and engineering estimates.

Temporal and Geographic Scope

As part of the data quality assessment, time period and geography were considered. All data submitted for ABS represent the years 2015 and/or 2016 and production in U.S. and Mexico. For the ABS resin primary data, companies were requested to provide data for the year 2015, the most recent full year of ABS 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. Three plants provided data for the year 2016, while another plant provided data from 2015. One of the data providers created SAN at a plant then transported it to a plant producing high graft rubber (HGR) where the HGR was extruded onto the SAN to produce ABS resin. After reviewing individual company data in comparison to the average, each manufacturer verified their ABS resin data was representative of an average year for ABS resin production at their company.

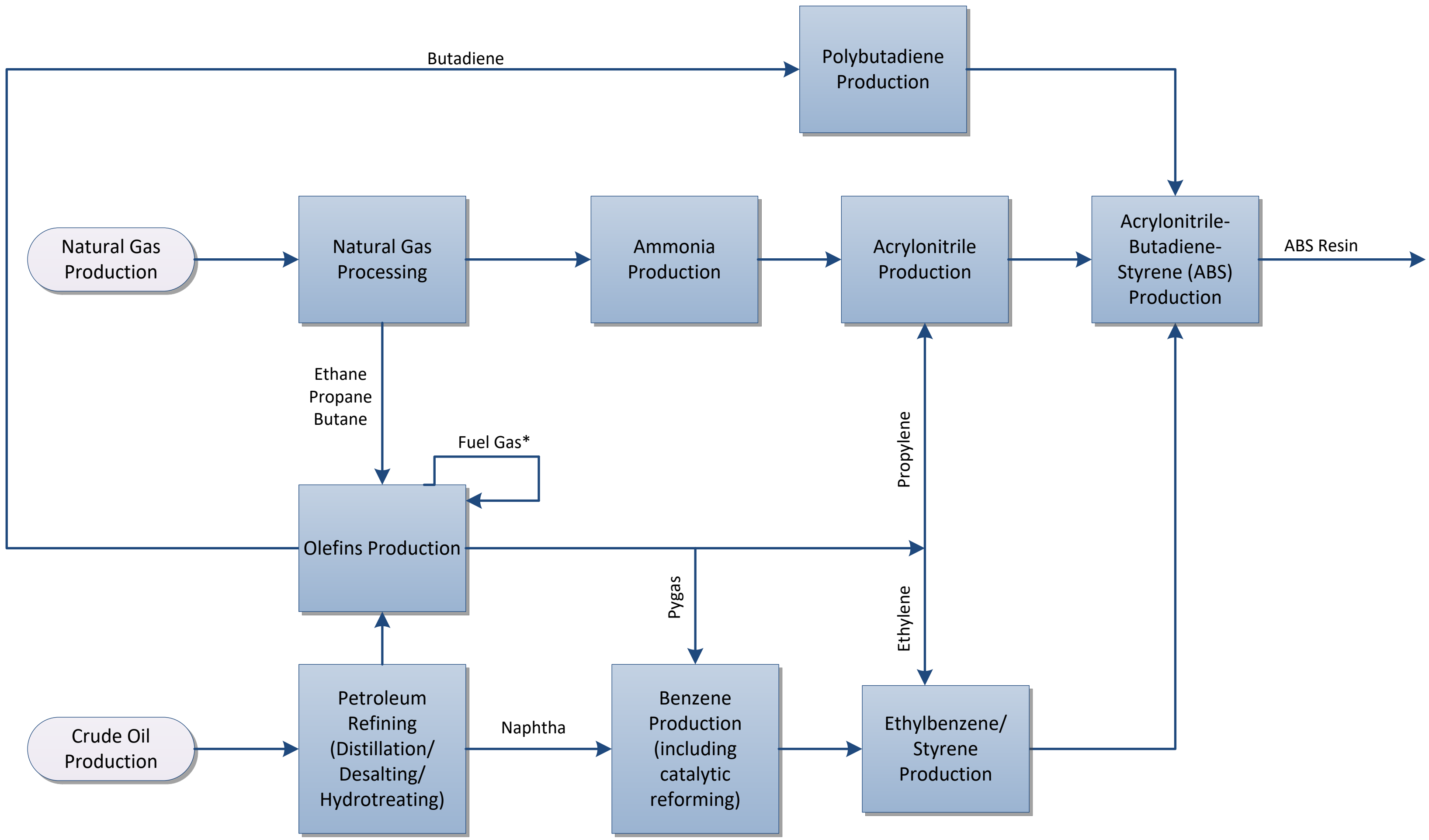

Figure 2. Flow diagram for the Production of Acrylonitrile Butadiene Styrene (ABS) Resin.

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

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.
Acrylonitrile data was collected from one plant and represents the year 2004. This data is not shown in the report to protect confidentiality.

The geographic scope of the analysis is the manufacture of ABS resin in North America. ABS 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.

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

- **Support personnel requirements**. The energy and wastes associated with research and development, sales, and administrative personnel or related activities have not been included in this study. Similar to space conditioning, energy requirements and related emissions are assumed to be quite small for support personnel activities.

INVENTORY AND IMPACT ASSESSMENT RESULTS CATEGORIES

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

The LCI and LCIA results categories and methods applied in this study are displayed in Table 1. This study addresses global, regional, and local impact categories. For most of the impact categories examined, the TRACI 2.1 method, developed by the United States Environmental Protection Agency (EPA) specific to U.S. conditions and updated in 2012, is employed.5 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.6 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).

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[5] 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.

[6] 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

- 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.

DATA SOURCES

The purpose of this study is to develop a life cycle profile for ABS resin using the most recent data available for each process. A production-weighted average was calculated for the ABS resin data (production for the year 2015 and 2016) collected for this analysis. The acrylonitrile data represents the year 2004 and was collected for the original study and represents only one plant, so is considered confidential and not shown in the appendix. 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. The energy data for ammonia was calculated from secondary sources and from stoichiometry, while transportation data, atmospheric emissions and solid wastes are estimates, and the waterborne emissions are from a 1970's source that were reviewed and revised in 1994. The polybutadiene data comes from secondary sources with the 1970s energy data reviewed for the original resins LCI study and AP-42 emissions data used from the 1990s. All included processes are shown in Figure 2.

LCI data for the production of ABS resin were collected from three producers (four plants) in North America within the United States and Mexico. All companies provided data for the years 2015 and/or 2016. A weighted average was calculated from the data collected and used to develop the LCA model. Only small amounts of off-spec product are coproducts of ABS 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.

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

The incoming material and fuel datasets for ABS 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.

Because new data was not provided for some of the upstream chemicals used to produce ABS and no higher quality secondary sources were found to update these datasets, some of the data is from older sources. 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. The energy data for ammonia was calculated from secondary sources and from stoichiometry, while transportation data, atmospheric emissions and solid wastes are estimates, and the waterborne emissions are from a 1970's source that were reviewed and revised. The polybutadiene data comes from secondary sources with the 1970s energy data reviewed by a producer at the time of the original resins LCI study and AP-42 emissions data used from the 1990s.

Consistency, Completeness, Precision: Data evaluation procedures and criteria were applied consistently to all primary data provided by the participating producers for all data collected. All primary data obtained specifically for this study were considered the most representative available for the systems studied. Primary data sets were reviewed for completeness and material balances, and follow-up was conducted as needed to resolve any

[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].

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: ABS resin manufactured in North America is commonly produced using emulsion or mass polymerization within the United States and Mexico. The three companies provided data from their facilities using technology ranging from average to state-of-the-art. Two of the producers use emulsion technology, while other stated mass polymerization is used. Each of the 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 that their data from 2015 or 2016 was representative of an average year for the plant and that the emulsion and mass polymerization technologies used were representative of production of ABS in North America.

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 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. 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 ABS 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

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

determined by the number of companies willing to participate. Data from this analysis was used to develop the most representative average for ABS resin production in 2015-2016 as was possible.

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

Order of Magnitude: In some cases, emissions data 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.

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 ABS resin, benzene, ethylbenzene/styrene, acrylonitrile and steam cracking of the olefins. All data received were carefully evaluated before compiling the production-weighted average data sets, as possible, 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. 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 each of the three main chemicals (ethylbenzene, acrylonitrile, and polybutadiene) used to produce ABS resin. The energy content of natural gas and petroleum used as raw material inputs for the production of the olefins (ethylene, propylene, butadiene, and pygas) used to produce ABS resin is included in the cradle-to-incoming material amounts in the energy results in this report. The energy inherent in these raw materials is called material feedstock energy. 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, acrylonitrile, and ABS resin 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 ABS resin production. The material coproducts from ethylene production for all plants included propylene, pyrolysis gasoline, butadiene, ethane, hydrogen, acetylene, crude benzene, and small amounts of various heavy end products. The material coproduct for styrene monomer included a small amount of toluene. The material coproducts from ABS 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).

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

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

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

Energy Coproducts Exported from System Boundaries

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

Electricity Grid Fuel Profile

Electricity production and distribution systems in North America are interlinked. Users of electricity, in general, cannot specify the fuels used to produce their share of the electric power grid. Data for this analysis was collected from plants in the United States 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.

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.

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

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

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%.

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

1. **Fuels consumed and emissions generated by the boiler:** The majority of data providers for this study reported natural gas as the fuel used for cogeneration. According to 2016 industry statistics, natural gas accounted for 75 percent of industrial cogeneration, while coal and biomass accounted for the largest portion of the remaining fuels used[11].

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

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

   The 50 percent conversion efficiency was an estimate after reviewing EIA fuel consumption and electricity net generation data from cogeneration plants in 2016.[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 amounts, which was divided by the efficiency and converted to natural gas amounts in cubic feet.

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

LIFE CYCLE INVENTORY AND IMPACT ASSESSMENT RESULTS

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

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 ABS:

- Cradle-to-incoming materials – includes the raw materials through the production of acrylonitrile, polybutadiene, and styrene.
- ABS 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 ABS 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-ABS and ABS system are interchangeable). The phrase "gate-to-gate" is defined as including only the onsite process/fuels.

ENERGY DEMAND

Cumulative Energy Demand

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

The average total energy required to produce ABS is 37.7 million Btu per 1,000 pounds of ABS resin or 87.7 GJ per 1,000 kilograms of ABS resin. Table 3 shows total energy demand for the life cycle of ABS resin production. The ABS resin production energy has been split out from the energy required for incoming materials, including the production of ethylbenzene/styrene monomer, acrylonitrile, polybutadiene, ammonia, benzene, olefins (ethylene/propylene/butadiene/pyrolysis gas), natural gas production and processing, and petroleum extraction and refining. Only 9.7 percent of the total energy is required to produce the ABS resin itself. The remaining 90 percent is used to create the incoming materials and their raw materials.

Table 3. Total Energy Demand for ABS Resin

	Basis: 1,000 pounds		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	MM Btu	***MM Btu***	***MM Btu***
Cradle-to-Incoming Materials	34.1	34.0	0.092
ABS Resin Production	3.66	3.54	0.13
Total	**37.7**	**37.5**	**0.22**
	Basis: 1,000 kilograms		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	GJ	***GJ***	***GJ***
Cradle-to-Incoming Materials	79.2	79.0	0.22
ABS Resin Production	8.52	8.23	0.29
Total	**87.7**	**87.2**	**0.51**
	Percentage		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	%	***%***	***%***
Cradle-to-Incoming Materials	90.3%	90.0%	0.25%
ABS Resin Production	9.7%	9.4%	0.34%
Total	**100%**	**99.4%**	**0.6%**

Non-renewable energy demand includes the use of fossil fuels (petroleum, natural gas, and coal) for process energy, transportation energy, and as material feedstocks (e.g., oil and gas used as feedstocks for the production of the olefins), as well as use of uranium to generate the share of nuclear energy in the average U.S. kWh. For the ABS resin, 99.4 percent of the total energy comes from non-renewable sources. The renewable energy demand consists of landfill gas used for process energy in olefins production and electricity derived from renewable energy sources (primarily hydropower, as well as wind, solar, and other sources). The renewable energy (0.29 GJ/1000 kg) used at the ABS 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 the olefins (ethylene, propylene, butadiene, and pygas) used to produce ABS 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 (87.7 GJ) for 1,000 kg of ABS resin, 50.3 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 ABS resin. Approximately 57 percent of the total energy is inherent energy in the natural gas and petroleum used as a feedstock to create the olefins, which in turn are used to create incoming materials to the ABS resin. Of the feedstock sources for the olefins and benzene, approximately 59 percent comes from natural gas, while 41 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 comes from oil.

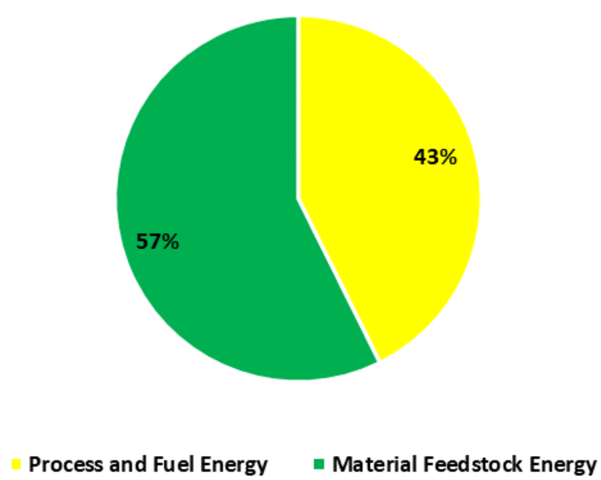

Figure 3. Process/Fuel and Material Feedstock Percentages for ABS Resin

Energy Demand by Fuel Type

The total energy demand by fuel type for ABS is shown in
Table **4** and the percentage mix is shown in Figure 4. Natural gas and petroleum together make up approximately 94 percent of the total energy used. As shown in Figure 3, this is partially due to the material feedstock energy used to create the olefins and other intermediate chemicals, which are inputs to ABS 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 ABS resin in the following table and figure represents the energy required for transportation of raw materials to ABS manufacturers, the energy required to produce the ABS resin, and the production of the fuels needed to manufacture the ABS.

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 ABS resin production shown in

Table **4** and Figure 4, 67 percent of the energy used (58.4 GJ/87.7 GJ) is from natural gas. At the ABS resin plant, 56 percent of the energy used (4.74 GJ/8.52 GJ) comes from natural gas. Of that natural gas used at the ABS resin plant, 58 percent is combusted on-site, while 42 percent is used to create electricity through the grid. Petroleum comprises approximately 27 percent (24 GJ/87.7 GJ) of the fuel used for the ABS resin production system. Over 80 percent of the petroleum used for the ABS 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 the inclusion of a small amount of landfill gas used in the olefins production shown within other renewables.

Table 4. Energy Demand by Fuel Type for ABS Resin

	Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable
	Basis: 1,000 pounds						
	MM Btu	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*
Cradle-to-Incoming Materials	34.1	23.1	10.1	0.51	0.34	0.036	0.057
ABS Resin Production	3.66	2.04	0.24	0.75	0.50	0.053	0.075
Total	**37.7**	**25.1**	**10.3**	**1.26**	**0.85**	**0.090**	**0.13**
	Basis: 1,000 kilograms						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	GJ	*GJ*	*GJ*	*GJ*	*GJ*	*GJ*	*GJ*
Cradle-to-Incoming Materials	79.2	53.6	23.4	1.18	0.79	0.084	0.13
ABS Resin Production	8.52	4.74	0.56	1.74	1.17	0.12	0.18
Total	**87.7**	**58.4**	**24.0**	**2.93**	**1.97**	**0.21**	**0.31**
	Percentage of Total						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	%	*%*	*%*	*%*	*%*	*%*	*%*
Cradle-to-Incoming Materials	90.3%	61.1%	26.7%	1.3%	0.9%	0.1%	0.2%
ABS Resin Production	9.7%	5.4%	0.6%	2.0%	1.3%	0.1%	0.2%
Total	**100%**	**67%**	**27%**	**3.3%**	**2.2%**	**0.2%**	**0.4%**

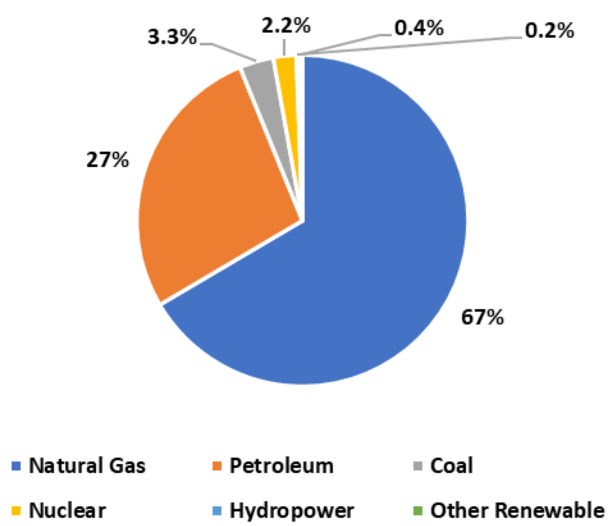

Figure 4. Percentage of Energy Separated by Fuel Type for ABS Resin

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 ABS 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 ABS 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 ABS plant. As shown in Figure 5, 37 percent of the total solid waste is associated with the ABS resin unit process. Seventy percent of this wastes associated with the ABS resin plant come from fuels combusted for the electricity used in the plant, while only 24 percent of the gate-to-gate ABS plant amount is process solid waste.

The larger portion of solid waste, 63 percent, comes from the production of incoming materials used to produce ABS resin. Natural gas and crude oil extraction with refining/processing are used to create the main input materials used in ABS resin. The solid wastes created from the extraction and processing of these raw materials create two-thirds of the solid wastes from the cradle-to-incoming materials. The coal extraction and combustion for the production of electricity accounts for 26 percent of the solid waste from incoming materials. The olefins and other input material plant process wastes make up the remaining 7 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 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. Less than 1 percent of the total solid wastes were considered hazardous wastes. Of that percentage, about half comes from the olefins plant and half from the ABS plant.

Table 5 also provides a breakout of the total solid wastes by the disposal fate. Of the hazardous waste (1 percent of total solid waste), a little less than 70 percent is incinerated without energy capture, while 20 percent is landfilled and 10 percent 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 3 percent is incinerated without energy capture and 2 percent is sent to waste-to-energy.

Table 5. Total Solid Wastes for ABS 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	73.1	0	0.46	0.008	0.47	0.001	3.69	68.9	72.6
Virgin ABS Resin Production	43.2	0.10	0.21	0.20	0.51	2.40	0.14	40.2	42.7
Total	**116**	**0.10**	**0.67**	**0.21**	**0.98**	**2.40**	**3.83**	**109**	**115**
	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	73.1	0	0.46	0.008	0.47	0.001	3.69	68.9	72.6
Virgin ABS Resin Production	43.2	0.10	0.21	0.20	0.51	2.40	0.14	40.2	42.7
Total	**116**	**0.10**	**0.67**	**0.21**	**0.98**	**2.40**	**3.83**	**109**	**115**
	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	63%	0%	0.4%	0.01%	0.4%	0.001%	3.2%	59%	62%
Virgin ABS Resin Production	37%	0.1%	0.2%	0.17%	0.4%	2.1%	0.1%	35%	37%
Total	**100%**	**0.1%**	**0.6%**	**0.18%**	**0.8%**	**2.1%**	**3.3%**	**94%**	**99%**

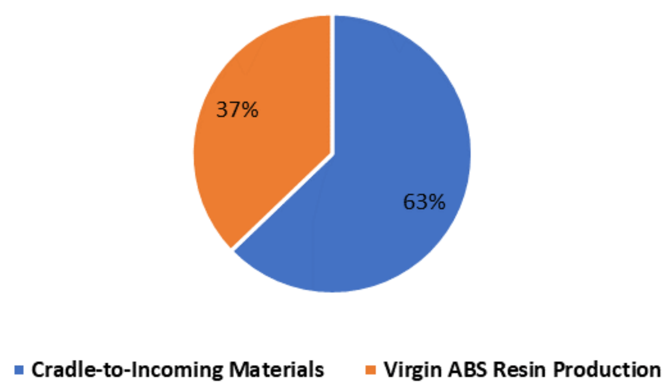

Figure 5. Percentage of Total Solid Wastes for ABS Resin System

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 attributed to hydropower generation does not include burdens for run-of the river hydroelectric plants. Run-of-the-river facilities produce power with no artificial reservoir and thus exhibit no water consumption burden (Lampert, 2015).

Water consumption results for ABS resin production are shown in Table 6 and Figure 6. The greatest portion of consumption of water within the ABS resin comes from the resin process itself (63 percent). The ABS resin average data includes some plants that release water to a different watershed, which is considered consumption in the methodology used. The ABS resin plant water consumption makes up approximately half of the total due to this. The remaining percentage of water consumption shown for the ABS resin plant is from hydropower used for electricity.

The processes leading to the resin production consume 37 percent of the water required. When looking at the individual unit processes, the primary water consumption data for olefins, which consumes 18 percent of the total, also includes some plants that release water to a different watershed than the initial water source. the natural gas extraction and processing and crude oil refining as a total comprise 9 percent of the total water consumption. Much of the remaining water consumption is from electricity used during all processes due to evaporative losses in the use of hydropower.

Table 6. Water Consumption for ABS Resin

	Total Water Consumption		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	Gallons	*Liters*	*%*
Cradle-to-Incoming Materials	653	5,445	37%
Virgin ABS Resin Production	1,135	9,469	63%
Total	**1,787**	**14,913**	**100%**

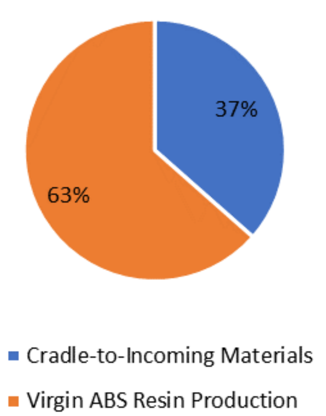

Figure 6. Water Consumption for ABS Resin

GLOBAL WARMING POTENTIAL

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

The 100-year global warming potential (GWP) factors for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2013[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 ABS resin system are displayed. Of the total, 82 percent of the GWP are attributed to emissions associated with production of the incoming materials, including natural gas and petroleum input materials, olefins, benzene, acrylonitrile, butadiene, and ethylbenzene/styrene with the remaining associated with the production of the ABS resin. More than half of the GWP of incoming materials is attributed to the cradle-to-styrene production, which also accounts for more than half of the incoming material by weight.

At the ABS resin production, 18 percent of the total GWP from greenhouse gases released during the production. The process greenhouse gases released at the ABS resin plants are less than 0.1 percent of the total; this is due to flaring, which is considered a mix of process and fuel-based emissions. Most of the remaining GWP from the ABS resin plants comes from electricity—mainly from the grid (59 percent of the ABS amount) or from cogeneration (33 percent of the ABS amount). While about 8 percent of the ABS resin GWP coming from fuel combustion for incoming transport of materials.

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.

Table 7. Global Warming Potential for ABS 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	2,354	2,354	82%
ABS Resin Production	524	524	18%
Total	**2,879**	**2,879**	**100%**

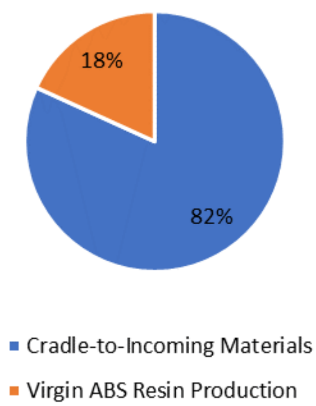

Figure 7. Global Warming Potential for ABS Resin

Error! Reference source not found. displays the cradle-to-gate ABS resin's GWP separated b y process contribution. This figure illustrates the percentages of GWP specific to process emissions at individual unit processes (e.g., styrene production), as well as to fuel-related emissions from the combustion of fuels and fuel combustion for transportation. Only processes creating at least one percent of the total GWP have been shown individually; all processes making up less than one percent 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 over 50 percent of the total GWP. The processing of incoming materials produces a little more than 20 percent of the GWP total, which comes directly from the release of greenhouse gases at the plants. This percentage includes the pie graph sections for styrene olefins and benzene, as well as a portion of the 2 percent for the remaining processes not shown. 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 18 percent of the total GWP. Transportation of the materials and fuels account for 8 percent of the total GWP.

Although the GWP from the ABS resin production is shown as 18 percent of the total in Figure 7, the majority of those emissions are combustion emissions, and so part of the 52 percent shown in Figure 8. The process greenhouse gases released at the ABS 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.

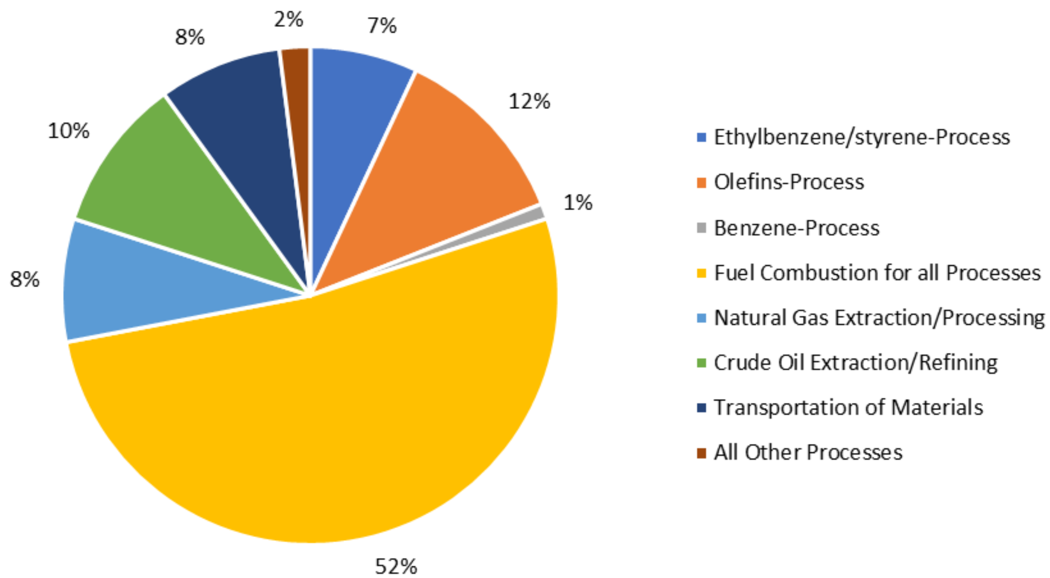

Figure 8. Global Warming Potential by Process Contribution

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). Extraction and processing emissions comprise 41 percent of the total AP, while total non-renewable combustion emissions make up 37 percent. Emissions specifically from the combustion of coal to generate grid electricity

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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.

is the largest single contributor (27 percent) to acidification impacts for the system. Combustion of transportation fuels and process emissions from many of the incoming intermediate chemicals production respectively make up 10 and 11 percent of the total AP.

Table 8 shows total acidification potential results for the ABS resin system. Results are shown graphically in Figure 9. In the AP category, 27 percent of the AP is coming from ABS resin production and about 73 percent comes from the raw and intermediate material unit processes. Only 0.2 percent of the total AP comes directly from the process emissions of the ABS resin production. Of the 27 percent AP shown in Table 9 for the virgin ABS resin production, 78 percent comes from electricity and 21 percent comes from transport.

Table 8. Acidification Potential for ABS Resin

	Acidification Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb SO2 eq	***kg SO2 eq***	***%***
Cradle-to-Incoming Materials	6.58	6.58	73%
Virgin ABS Resin Production	2.44	2.44	27%
Total	**9.01**	**9.01**	**100%**

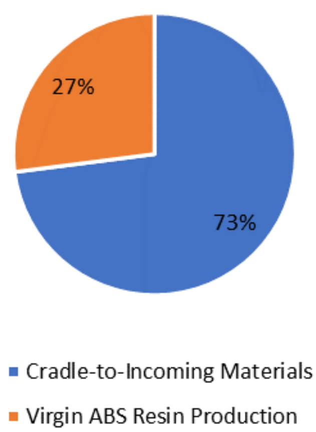

Figure 9. Acidification Potential for ABS Resin

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 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. For the ABS resin total EP results, nitrogen oxides accounts for 71 percent, 12 percent comes from COD, 5 percent is from BOD and 5 percent comes from phosphoric acid.

Eutrophication potential (EP) results for ABS resin are shown in Table 9 and illustrated in Figure 10. The largest portion, 79 percent, of the EP results are associated with the production of the raw and intermediate materials used to create ABS resin. The extraction and processing/refining of natural gas and oil for materials and fuels releases 40 percent of the EP impact, which are all within the cradle-to-incoming materials amount. Also, part of the cradle-to-incoming materials EP, the various intermediate plant process emissions comprise 27 percent of the EP impact results. The combustion of non-renewable fuels in boilers, equipment and transport creates 25 percent of the EP total; these are part of both the ABS resin production and all raw and intermediate materials.

The gate-to-gate ABS resin production generates 21 percent of the EP impact, with a little less than half of that percentage from electricity use and 24 percent representing the combustion of fuels for transport. Six percent of the total EP impact comes from process emissions released at the ABS plant.

Table 9. Eutrophication Potential for ABS Resin

	Eutrophication Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb N eq	***kg N eq***	***%***
Cradle-to-Incoming Materials	0.37	0.37	79%
Virgin ABS Resin Production	0.097	0.097	21%
Total	**0.47**	**0.47**	**100%**

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

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.

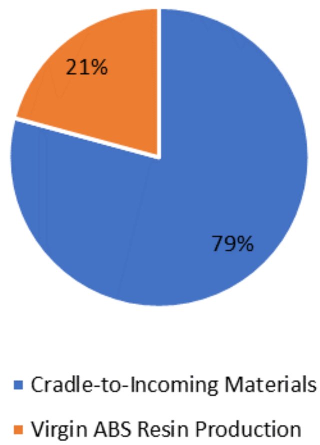

Figure 10. Eutrophication Potential for ABS Resin

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., HCFCs 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 ABS 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 and benzene, and some are associated with small leaks of refrigerants used.

Table 10 shows total ODP results for the ABS resin system, which are also shown graphically in Figure 11. Ozone depletion results for the ABS resin system (87 percent of the total) are dominated by a small amount of refrigerant reported by less than 3 of the ABS 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. The ODP amount shown in the cradle-to-incoming materials include emissions from crude oil extraction and refining, which contributes 13 percent of the total ozone depletion impacts.

Table 10. Ozone Depletion Potential for ABS 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	7.2E-06	7.2E-06	13%
Virgin ABS Resin Production	5.0E-05	5.0E-05	87%
Total	**5.7E-05**	**5.7E-05**	**100%**

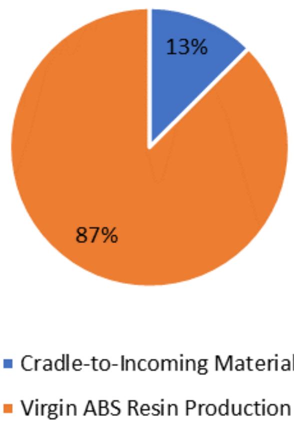

Figure 11. Ozone Depletion Potential for ABS Resin

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 ABS, NO_x makes up over 90 percent of the smog formation emissions, with VOCs consisting of 9 percent.

[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 ABS resin are displayed in Table 11 and illustrated in Figure 12. Approximately 81% of the POCP impact results are associated with production of the raw and intermediate materials. The process emissions from the intermediate chemicals create 13 percent of the total POCP. Almost half of the total POCP impact results are from the natural gas and oil extraction and processing/refining. The combustion of fuels in boilers, equipment, and for transport release emissions that create 34 percent of the total POCP amount, which would be included in both the ABS resin portion and the incoming materials.

The remaining 19 percent of the POCP impact is from ABS resin production. Of that percentage, almost two-thirds of the POCP amount for the ABS resin plant comes from the generation of electricity used in the plant, which includes the combustion of natural gas and coal at power plants and combustion of natural gas in cogeneration plants. One third of the POCP is from the transport of incoming materials. Only 1 percent of the ABS resin plant emissions resulting in the POCP impact results are released as process emissions.

Table 11. Photochemical Smog Formation Potential for ABS 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	166	166	81%
Virgin ABS Resin Production	38.3	38.3	19%
Total	**204**	**204**	**100%**

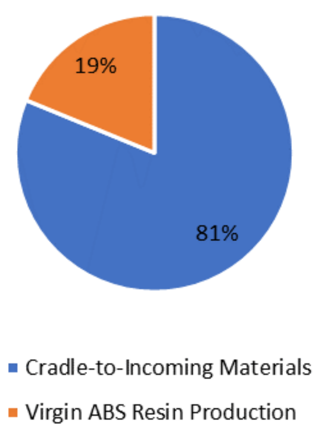

Figure 12. Photochemical Smog Formation Potential for ABS Resin

COMPARISON OF 2022 AND 2011 LCI AND LCIA ABS RESULTS

This section provides a comparison of life cycle inventory and impact assessment category results that were included in the original virgin ABS 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 2021 ABS 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 total. 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 differences between the two averaged datasets are partially due to the use of different or additional companies and manufacturing plants when updating the olefins, styrene, and ABS 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, ABS 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. Also, the number of companies participating in this update for the ABS resin remained at 3; however, only one plant that participated in collecting data for the previous analysis provided data for 2015-2016.

The decrease in energy, solid waste, and GWP over time is significant. Much of this is due to the large decrease in the average amount of styrene required to produce ABS. The styrene amount decreased by almost 100 kg per 1000 kg of ABS produced. The producers were asked if over the past 10 years there have been technological or efficiency changes that allowed for the styrene amount to be decreased. Two of the producers did respond that there have been improvements and decreases in styrene amounts. Another possibility is that each ABS product has formula specifications on the amounts of styrene acrylonitrile versus the polybutadiene (rubber portion) allowed for their product. If the ABS products have changed over time or have changed for the plants providing data currently versus those from 2004, and less styrene acrylonitrile and more rubber is required, this would affect the average.

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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 2021 LCI and LCIA Results for Virgin ABS Resin

	1000 pounds of Virgin Acrylonitrile Butadiene Styrene 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*
ABS 2022	37.7	37.5	0.22	115	2,879
ABS 2011	45.2	44.8	0.34	200	3,805
	1000 kilograms of Virgin Acrylonitrile Butadiene Styrene 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*
ABS 2022	87.7	87.2	0.51	115	2,879
ABS 2011	105	104	0.79	200	3,805
Percent Decrease	18%	18%	43%	54%	28%

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

When the formulation of the 3 incoming materials are compared over time, the acrylonitrile and polybutadiene both increased by 2 percent, while the styrene amount decreased by 5 percent. Overall, the formulation by weight percent did not change significantly. Higher amounts of styrene do seem to be used by the mass polymerization compared to the emulsion polymerization. The data provided includes both technologies, and potentially some of the decrease may be from the differences in the plants collecting data and the weighting of those plants to create the average.

ENERGY COMPARISON

Overall, the total energy for ABS resin has decreased 17.3 GJ on a 1,000 kg basis (7.5 MMBtu/1,000 lb). There is a 17 percent decrease in total energy as compared to the original results. This percentage is larger than differences seen in most of the resins over time and much of the difference revolves around the lower styrene input amount, although the energy required at the ABS resin plant itself did decrease by a sizable percentage as well. When comparing the ABS resin unit process average energy data, the average electricity amount did decrease while the natural gas usage increased; however, in the previous average, coal was used to some degree which has been replaced by NG, which is a cleaner fuel. A decrease in total energy for ABS resin is also attributed to decreases in energy use for extraction and processing/refining of natural gas and oil and within the olefins plant itself. Because olefins are material inputs into each of the chemicals used to produce ABS resin, the overall energy decrease for the olefins contributes to the larger decrease in the energy use for incoming materials to ABS resin as compared to the 2011 study.

Certainly, the addition of different plants into the analysis 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.

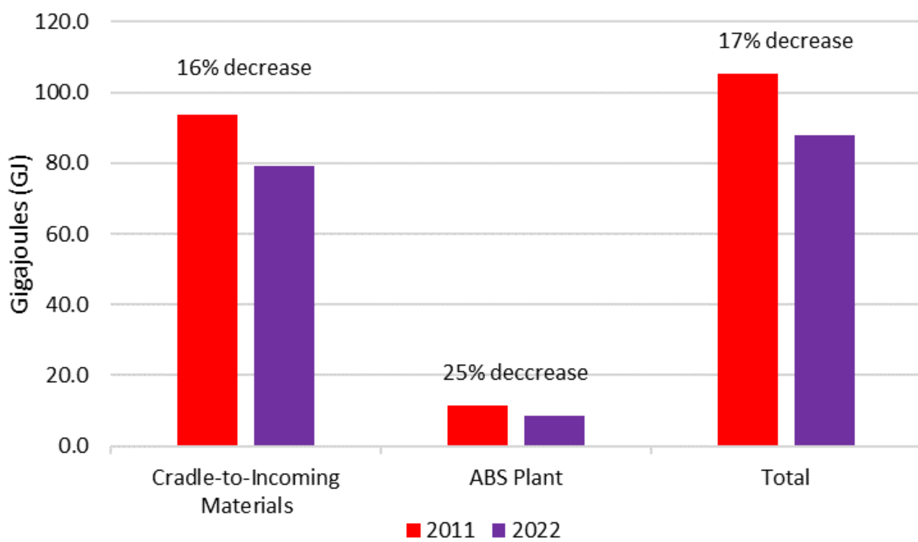

Figure 13. Change in Energy by Stage per 1,000 kg (GJ/1000 kg)

The energy of material resource, which pertains to the amount of inherent energy from the raw materials decreased by a small amount for ABS resin mainly due to the decrease in styrene input compared to the data in the 2011 report. The total decrease is also due in part to the energy decreases in the energy requirements for the olefins plants which play a large part of the intermediate chemical production, as well as the oil and natural gas extraction and processing/refining.

The percent difference in renewable energy decreased about 43 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 ABS, including the ABS resin unit process itself, 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 most processes required to manufacture ABS.

SOLID WASTE COMPARISON

When compared to the 2011 ABS resin total solid waste amount, the current ABS resin study shows 85 kg per 1000 kg ABS resin less solid waste, which is a 42 percent decrease, much lower than 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 2021 reports. Figure 14 provides a visual of the total solid waste amount split out by the ABS unit process and cradle-to-incoming materials. In the previous study, the solid waste created was split almost evenly between the ABS resin production and the incoming materials; however now this split is closer to two-thirds from the raw and intermediate materials and one-third from the ABS plant. The large solid waste decrease, more than half, at the ABS plant is mainly due to the decrease in electricity use and change of boiler fuel overall. The use of coal to create electricity and previously as a boiler fuel produced a high amount of ash that requires discarding; therefore, the decrease of electricity and change from coal to natural gas boiler fuel has brought down the amount of solid waste created. Also at the ABS resin plant, the process waste decreased by about 20 percent. The decrease in amount of 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.

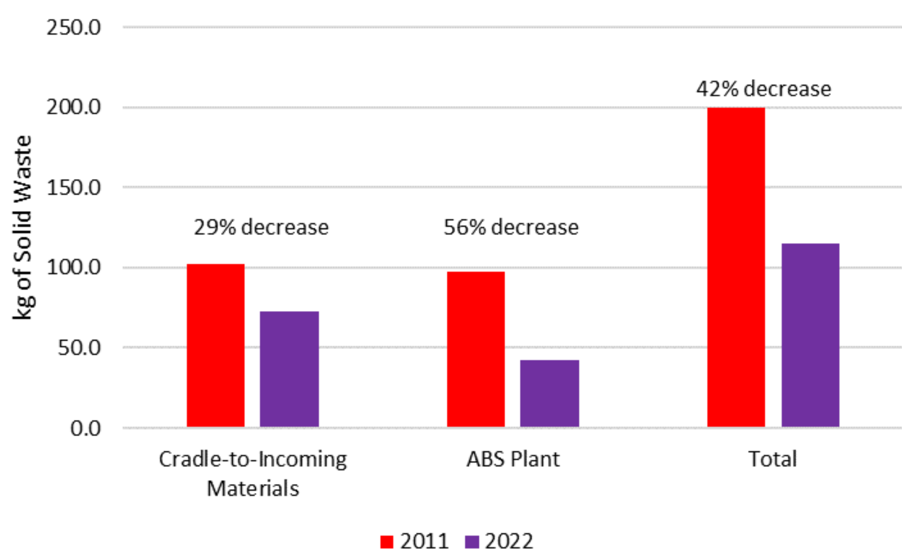

Figure 14. Change in Solid Waste Weight by Stage (kg Per 1,000 kg)

GLOBAL WARMING POTENTIAL COMPARISON

The total global warming potential decreased by 926 kg CO_2 equivalents/1000 kg ABS resin, which calculates to a 24 percent decrease. Figure 15 displays a column chart with the ABS resin and cradle-to-incoming materials results that makeup the decrease when comparing the 2011 and 2021 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.

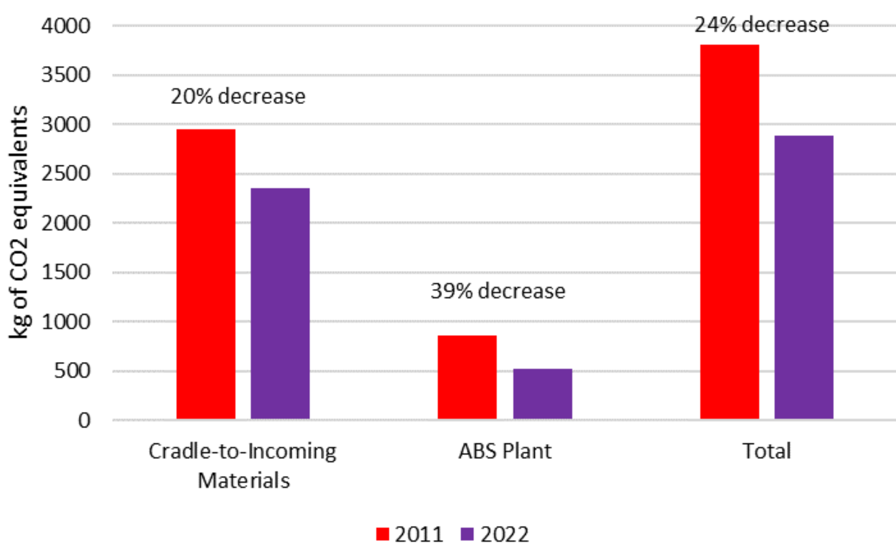

Figure 15. Change in Global Warming Potential by Stage (kg of CO2 eq. per 1,000 kg)

The GWP specific to the ABS resin plant decreased by 39 percent, while the energy for the plant also decreased. This decrease in GWP is expected as most of the potential is created from fuel combustion. As stated in the energy comparison section, the amount of electricity required at ABS resin production is lower in 2015. Also, the fuel mix for the boiler changed from coal/natural gas to only natural gas. The combustion of coal releases higher amounts of greenhouse gas than the combustion of natural gas. Greenhouse gases released as process emissions are less than 1 percent of the total GWP for the ABS resin plant, so all the GWP decrease shown is from fuel combustion.

The decrease in GWP for the cradle-to-incoming materials comes from decreases in energy use for the raw materials (natural gas and oil) and for most of the intermediate (olefins) and other incoming materials to the ABS 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. Another reason for this large decrease is the amount of styrene required to be produced has declined due to the weighted average formulation from the ABS resin plants.

APPENDIX: ACRYLONITRILE BUTADIENE STYRENE (ABS) MANUFACTURE

This appendix discusses the manufacture of acrylonitrile butadiene styrene (ABS) resin. ABS is used to make a variety of products by way of extrusion or injection molding. Common end use applications include automotive panels and trim, keyboards, refrigerator liners, and pipes/fittings. The captured ABS production percentage of the total ABS production in North America in 2015 is unknown as it was not reported separately in The Resin Review (ACC, 2016) and was not found in other sources. The material flow for ABS 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 processes are included in this appendix:

- Polybutadiene
- Acrylonitrile
- Acrylonitrile butadiene styrene resin production

LCI data for olefins (ethylene, propylene, butadiene, and pygas), ethylbenzene/styrene, and ABS production were collected for this update to the U.S. LCI plastics database by member companies of the American Chemistry Council. Benzene and acrylonitrile plant data were not updated from the original resins report; however, the input materials were updated. Secondary data was used for crude oil extraction and refining and natural gas production and processing, ammonia, and polybutadiene. LCI data for the production of olefins, oil, and natural gas can be found in the report, ***Cradle-to-Gate Life Cycle Analysis of Olefins, Final Report***. LCI data for the production of benzene and ethylbenzene/styrene are found in the report, ***Cradle-to-Gate Life Cycle Analysis of General Purpose Polystyrene, Final Report***. LCI data for the production of ammonia are found in the report, ***Cradle-to-Gate Life Cycle Analysis of Methylene Diphenyl Diisocyanate (MDI), Final Report***.

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).

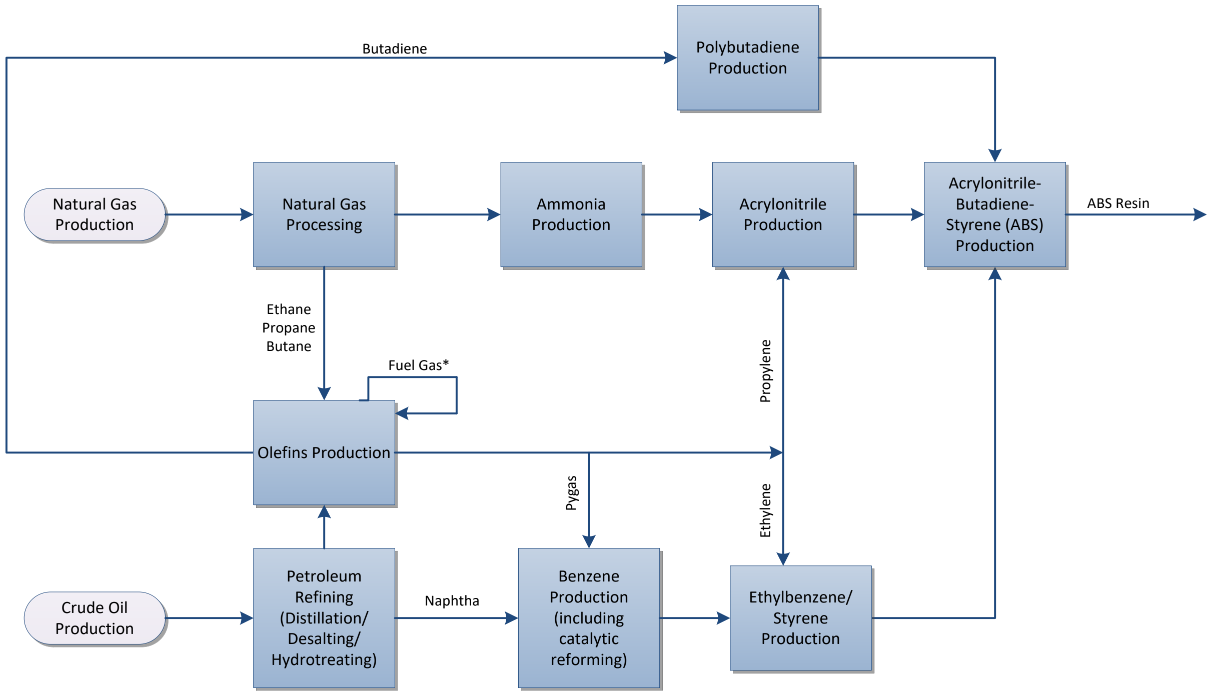

Figure 16. Flow diagram for the Production of Acrylonitrile butadiene styrene (ABS) Resin.

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

The removal of hydrogen from butane/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 13. No newer 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 13. 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.

ACRYLONITRILE PRODUCTION

Acrylonitrile production in the U.S. and most of the world is based on the Sohio process. Propylene, air, and ammonia are catalytically converted to acrylonitrile using a fluidized bed reactor. Operating temperatures of the rector are 350˚ to 510 ˚ Celsius and gauge pressures are 30 to 200 kPa (Deepa, 2016). Following the reactor phase, gaseous products are subject to water absorption to remove inert gases and recovered products are sent to a fractionator to remove hydrogen cyanide. Following fractionation, acrylonitrile is separated from acetonitrile by extraction. The reaction is exothermic with recovered heat being used to generate steam for use in the process. The chemical equation for the process is:

$$2CH2=CH\text{-}CH3 + 2NH3 + 3O2 \rightarrow 2CH2=CH\text{-}CN + 6H2O$$

Major by-products are hydrogen cyanide and acetonitrile, which are normally incinerated because supply often exceeds demand. Unused ammonia can be recovered as ammonium sulfate and then disposed of, but it is commonly vented to the atmosphere (Kent, 2003).

The energy and emissions data for acrylonitrile production is from a confidential source and is not shown to protect its confidentiality (Primary Data, 2004). The company provided ranges for the material inputs and coproducts. The median of these ranges was used in the acrylonitrile dataset. Hydrogen cyanide and acetonitrile are produced as coproducts during this process. A mass basis was used to partition the credit for these coproducts. Waterborne emissions from the confidential dataset collected for acrylonitrile are sent to deepwell disposal, which is not included as the emissions are not released to a water source.

ACRYLONITRILE BUTADIENE STYRENE (ABS) PRODUCTION

Two standard technologies for ABS production in North America are emulsion or mass polymerization. Both of these technologies are represented within the ABS production dataset.

Manufacture of ABS using emulsion technology includes grafting styrene and acrylonitrile onto a polybutadiene matrix. The basic steps in the emulsion process include polybutadiene polymerization in an aqueous emulsion using initiators and emulsifiers, high-graft rubber (HGR) polymerization and product separation, polymerization of styrene acrylonitrile (SAN) and processing/compounding of the final product. Mass ABS polymerization is a continuous process and includes pre-polymerization, polymerization, devolatilization, and extrusion. Mass polymerization generates a minimum of wastewater and eliminates the need for dewatering and drying. In both the emulsion and mass processes the polybutadiene must be soluble in styrene. Polybutadiene resin may be added as a dry resin rather than a latex.

An individual weighted average for three leading ABS resin producers (four plants) in the United States was calculated using the production amounts from each plant for ABS resin. All companies provided data for the years 2015 or 2016. A weighted average was calculated from the data collected and used to develop the LCA model. Only small amounts of off-spec product is a coproducts of ABS resin production, and a mass basis was used to allocate the environmental burdens for the coproducts.

ABS resin producers from the United States and Mexico provided data from their facilities using technology ranging from average to state-of-the-art. The producers stated they use either mass or emulsion polymerization.

Primary data were collected from ABS manufacturers from the year 2016 (three plants) and 2015 (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 ABS production in North America.

Data providers reviewed their data as well as the average ABS 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 14 shows the averaged energy and emissions data for the production of 1,000 pounds and 1,000 kilograms of ABS resin. In the case of many of the 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. As shown in Table 14, total raw material inputs for the production of ABS are less than outputs due to additives and modifiers that are used in the manufacture of ABS but not shown in the table.

Table 14. LCI Data for the Production of Acrylonitrile Butadiene Styrene (ABS) Resin

	1,000 lb		1,000 kg		
Material Inputs					
Ethylbenzene styrene	576	lb	576	kg	
Polybutadiene	156	lb	156	kg	
Acrylonitrile	225	lb	225	kg	
Energy					
Process Energy					
Electricity from grid	228	kWh	503	kWh	
Natural gas	1,121	ft^3	70.0	m^3	
Liquid petroleum gas (LPG)	1.1E-05	gal	8.8E-05	l	
Gasoline	3.2E-06	gal	2.7E-05	l	
Diesel	4.8E-06	gal	4.0E-05	l	
Transportation Energy					
Truck	28.6	ton·mi	92.0	tonne·km	
Rail	24.9	ton·mi	80.0	tonne·km	
Barge	205	ton·mi	660	tonne·km	
Pipeline -refinery products	0.0075	ton·mi	0.024	tonne·km	
Ocean freighter	140	ton·mi	450	tonne·km	
Environmental Emissions					
Atmospheric Emissions					
Carbon monoxide	0.0010	lb	0.0010	kg	*
Methane, chlorodifluoro-, HCFC-22	0.0010	lb	0.0010	kg	*
NMVOC, non-methane volatile organic compounds, uns	0.0010	lb	0.0010	kg	*
Nitrogen oxides	0.010	lb	0.010	kg	*
Sulfur oxides	1.0E-04	lb	1.0E-04	kg	*
Particulates, < 2.5 um	1.0E-05	lb	1.0E-05	kg	*
Particulates, > 2.5 um, and < 10um	1.0E-04	lb	1.0E-04	kg	*
Ammonia	1.0E-04	lb	1.0E-04	kg	*
Methane	1.0E-05	lb	1.0E-05	kg	*
Styrene	0.019	lb	0.019	kg	
Acrylonitrile	0.014	lb	0.014	kg	
Xylene	1.0E-04	lb	1.0E-04	kg	*
Cumene	0.0010	lb	0.0010	kg	*
Acetophenone	0.0010	lb	0.0010	kg	*
Methyl methacrylate	1.0E-04	lb	1.0E-04	kg	*
Benzene, ethyl-	0.016	lb	0.016	kg	
Butadiene	0.010	lb	0.010	kg	*
Carbon dioxide	1.00	lb	1.00	kg	*

Table 15. LCI Data for the Production of Acrylonitrile Butadiene Styrene (ABS) Resin (Continued)

	1,000 lb		1,000 kg		
Waterborne Releases					
Fluoride					
BOD5, Biological Oxygen Demand	0.0010	lb	0.0010	kg	*
COD, Chemical Oxygen Demand	0.010	lb	0.010	kg	*
Suspended solids, unspecified	0.10	lb	0.10	kg	*
Dissolved solids	0.10	lb	0.10	kg	*
Hydrogen chloride	0.010	lb	0.010	kg	*
Oils, unspecified	0.010	lb	0.010	kg	*
Phosphoric acid	0.0010	lb	0.0010	kg	*
Cyanide	0.010	lb	0.010	kg	*
Suspended solids, unspecified	1.0E-05	lb	1.0E-05	kg	*
Zinc	0.10	lb	0.10	kg	*
Chromium	1.0E-05	lb	1.0E-05	kg	*
Iron	1.0E-05	lb	1.0E-05	kg	*
Nickel	1.0E-04	lb	1.0E-04	kg	*
Mercury	1.0E-05	lb	1.0E-05	kg	*
Lead	1.0E-06	lb	1.0E-06	kg	*
Arsenic	1.0E-05	lb	1.0E-05	kg	*
Barium	1.0E-06	lb	1.0E-06	kg	*
Chlorine	1.0E-04	lb	1.0E-04	kg	*
Copper	1.0E-05	lb	1.0E-05	kg	*
Manganese	1.0E-05	lb	1.0E-05	kg	*
Selenium	1.0E-05	lb	1.0E-05	kg	*
Methanol	1.0E-05	lb	1.0E-05	kg	*
Ethylene glycol	1.0E-04	lb	1.0E-04	kg	*
Benzothiazole	1.0E-05	lb	1.0E-05	kg	*
Styrene	1.0E-03	lb	1.0E-03	kg	*
Acrylonitrile	1.0E-04	lb	1.0E-04	kg	*
1,2,4-Butanetricarboxylic acid, 2-phosphono-	1.0E-05	lb	1.0E-05	kg	*
Solid Wastes					
Solid waste, process to landfill	8.00	lb	8.00	kg	
Solid waste, process to incineration	0.14	lb	0.14	kg	
Solid waste process, to WTE	2.40	lb	2.40	kg	
Hazardous waste to landfill	0.20	lb	0.20	kg	
Hazardous waste to incineration	0.21	lb	0.21	kg	
Hazardous waste sold for recycling or reuse	0.74	lb	0.74	kg	
Hazardous waste to WTE	0.10	lb	0.10	kg	
Water Consumption	887	gal	7,400	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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