Final Report

Life Cycle Assessment of Vinyl Ester Resin, Polyurethane Precursors, and Pultrusion

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Preface

This Life Cycle Inventory (LCI) study was conducted for the American Composites Manufacturers Association (ACMA). The report was made possible through the cooperation of ACMA member companies, who provided data for the production of vinyl ester resin and the pultrusion process.

Eastern Research Group, Franklin Associates Division, carried out the work as an independent contractor for this project. Emily Wexler and Paige Weiler were the primary analysts whose tasks included researching, collecting and compiling the LCI data, and authoring the report. Melissa Huff, Senior LCA Analyst was Project Manager and oversaw collection and compilation of the LCI data, authoring sections of the report, as well as providing technical and editorial review.

Franklin Associates gratefully acknowledges the significant contribution to this project by John Schweitzer of ACMA in leading this project. Thank you to the companies who graciously provided data. Their effort in collecting data has added considerably to the quality of this LCA report.

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TERMS AND DEFINITIONS (ALPHABETICAL)

Acidification Potential— potential of emissions such as sulfur dioxide and nitrogen oxides to result in acid rain, with damaging effects on ecosystems and buildings.

Allocation—partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.

Characterization Factor—factor derived from a characterization model which is applied to convert an assigned life cycle inventory analysis result to the common unit of the category indicator.

Combustion Energy—the higher heat value directly released when coal, fuel oil, natural gas, or biomass is burned for energy consumption.

Co-product—any of two or more products coming from the same unit process or product system.

Cradle-to-Gate—refers to an LCA or LCI covering life cycle stages from raw material extraction through raw material production (i.e., does not cover entire life cycle of a product system).

Cradle-to-Grave—an LCA or LCI covering all life cycle stages of a product system from raw material extraction through end-of-life and recycling when applicable.

End-of-Life—refers to the life cycle stage of a product following disposal.

Energy Demand—energy requirements of a process/product, including energy from renewable and non-renewable resources). In this study, energy demand is measured by the higher heating value of the fuel at point of extraction.

Energy of Material Resource—the energy value of fuel resources withdrawn from the planet's finite fossil reserves and used as material inputs. Some of this energy remains embodied in the material and can potentially be recovered. Alternative terms used by other LCA practitioners include "Feedstock Energy" and "Inherent Energy."

Eutrophication Potential—assesses the potential of nutrient releases to the environment to decrease oxygen content in bodies of water, which can lead to detrimental effects such as algal blooms and fish kills.

Fossil Fuel—fuels with high carbon content from natural processes that are created over a geological time frame. Natural gas, petroleum and coal are examples of fossil fuels.

Fugitive Emissions—unintended leaks of substances that escape to the environment without treatment. These are typically from the processing, transmission, and/or transportation of fossil fuels, but may also include leaks and spills from reaction vessels, other chemical processes, methane emissions escaping untreated from landfills, etc.

Functional Unit—quantified performance of a product system for use as a reference unit.

Global Warming Potential—an index, describing the radiative characteristics of well-mixed greenhouse gases, which represents the combined effect of the differing times these gases remain in the atmosphere and their relative effectiveness in absorbing outgoing infrared radiation. This index approximates the time-integrated warming effect of a unit mass of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide.[1]

Greenhouse Gas—gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds. This property causes the greenhouse effect. Water vapor, carbon dioxide, nitrous oxide, methane, and ozone are the primary greenhouse gases in the Earth's atmosphere.

Impact Category—class representing environmental issues of concern to which life cycle inventory analysis results may be assigned.

Life Cycle—consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.

Life Cycle Assessment—compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life Cycle Inventory—phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Life Cycle Impact Assessment—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.

Life Cycle Interpretation—phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

Non-Renewable Energy—energy from resources that cannot be created on scale to sustain consumption. Fossil fuels (e.g., coal, petroleum, natural gas) and nuclear power (uranium) are considered non-renewable energy resources.

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[1] Definition from the glossary of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report - Climate Change 2001.

Ozone Depletion Potential—the potential to destroy ozone based on a chemical's reactivity and lifetime. Some of the main sources of emissions contributing to ODP are minute amounts of tetrachloromethane, HCFCs, and halons.

Photochemical Ozone Creation Potential—the potential of airborne emissions to cause photochemical smog. The creation of photochemical smog occurs when sunlight reacts with NOx and volatile organic compounds (VOCs), resulting in tropospheric (ground-level) ozone and particulate matter.

Process Waste—wastes from processes along the entire life cycle of the product system. Does not include postconsumer waste.

Renewable Energy—energy from natural resources that can be replenished (e.g., biomass) or are not depleted by use (e.g., hydropower, sunlight, wind).

Solid Waste—any wastes resulting from fuel extraction and combustion, processing, or postconsumer disposal. Solid waste in this study is measured as waste to a specific fate (e.g., landfill, incinerator).

System Boundary—set of criteria specifying which unit processes are part of a product system.

Transportation Energy—energy used to move materials or goods from one location to another throughout the various stages of a product's life cycle

Unit Process—smallest element considered in the life cycle inventory analysis for which input and output data are quantified.

Water Consumption—consumptive use of water 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.

CHAPTER 1. STUDY GOAL & SCOPE/METHODOLOGY

INTRODUCTION

This study provides the American Composites Manufacturers Association (ACMA), 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 three input materials used in composite manufacturing and for one manufacturing process. The composite materials studied are vinyl ester resin (VER) and two precursor materials used in the production of polyurethane resin (PUR), a common input material to products made from composites. The two PUR precursors studied are those used for rigid PUR: methylene diphenyl diisocyanate (MDI) and polyether polyol. The analysis also includes an average dataset for the pultrusion process. The pultrusion process is used by a large number of companies to produce a wide variety of composites products using different types of input materials. The analysis of the pultrusion average described in this report is based on data from a limited number of companies and may not represent specific types of pultruded products. More information has been provided in the section discussing data representativeness. The data collected for the materials and pultrusion process are representative of production within the United States.

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.

Life cycle assessment (LCA) is recognized as a scientific method for making comprehensive, quantified evaluations of the environmental benefits and tradeoffs for the entire 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 as shown in Figure 1 below. However, as the goal of this analysis is to create average results for the production of materials or various products from pultrusion that may be used in unknown processes or products downstream, the boundaries of the analysis have been set to cradle-to-gate. The two dashed boxes indicate the boundaries included in this analysis. The inner dashed box is representative of the materials, and the outer representative of the process employing those materials to manufacture products.

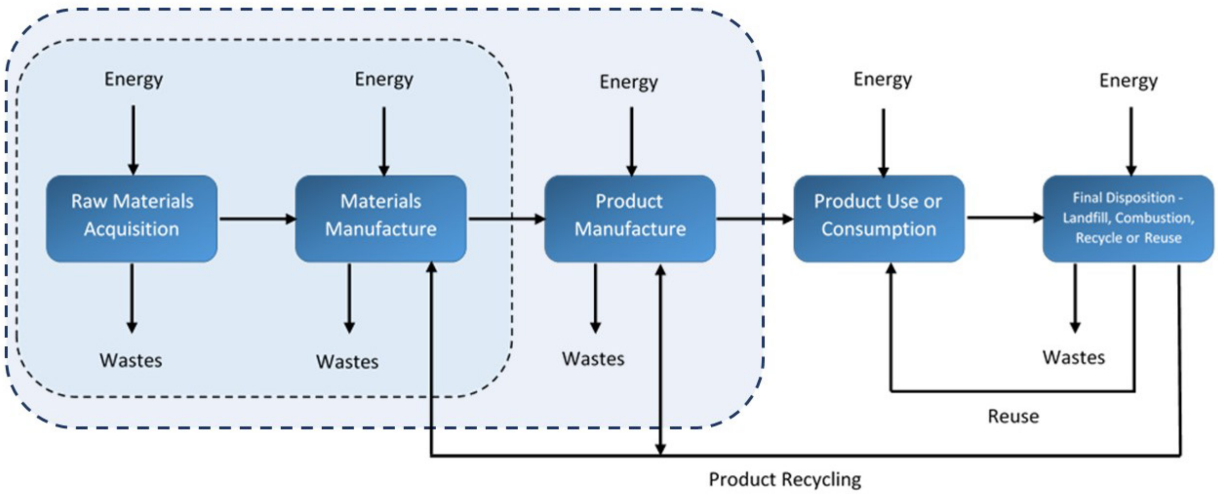


FIGURE 1. GENERAL MATERIALS FLOW FOR "CRADLE-TO-GRAVE" ANALYSIS OF A PRODUCT SYSTEM.

The method used for this life cycle inventory (LCI) and life cycle impact assessment 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[2]

For this LCA, the boundary ends at product manufacture. In the analyses described here, the considered products are VER, PUR precursors, and composites products made using the pultrusion process. 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 average LCI data for each material's unit processes and the pultrusion unit process are provided in each chapter. The VER and pultrusion unit process LCI data will be made available to the National Renewable Energy Laboratory (NREL) who maintains the U.S. LCI Database. The PUR precursors are already in the U.S. LCI Database per the ACC.

[2] 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.

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 that lead to that impact are multiplied by a characterization factor that expresses the impact of each substance relative to the reference substance. Once each emission amount is normalized to a specific impact unit (e.g., CO_2 equivalents for Global Warming), they are summed to a total for each impact category.

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 goal of this study is to conduct a transparent Life Cycle Inventory (LCI) and then evaluate the environmental profile of the materials and process included in this study. The intended use of the study results is twofold:

1. To provide ACMA and its members with an average LCI unit process data for vinyl ester resin production and the pultrusion process that are an average of the data provider's operations for submission to the US LCI Database so that the LCI data may be used by public and private stakeholders, and

2. Provide the ACMA and their members with - LCI/LCIA results representative of the cradle-to-gate production of the composites input materials (VER, MDI, and Polyol for Rigid PUR) and the pultrusion process for their use as an internal benchmarking and decision-making resource.

According to ISO 14040 and 14044 standards, a critical or peer review is not required to meet the standards as no comparative assertions of competing materials or products are made in this study.

ACMA members may use the information from this LCI as the basis for further study of any potential improvement of resource use and environmental emissions associated with the composite input materials and the pultrusion process.

The materials manufacturing data sets developed in the project can be combined to model a wide variety of composites products. By making these data sets publicly available through the U.S. LCI Database, ACMA has provided valuable resources to support consistent, transparent modeling of composites products by any interested party.

Functional Unit

To provide a basis for comparison of different products, a common reference unit must be defined. The reference unit is commonly based upon the function of the products, so that comparisons of different products are made on a uniform basis. In the case of materials, such as VER or PUR precursors, which are included in formulations to create various composites products, a mass basis allows the producer using the material to easily include the specific amount of material within their product. In the case of pultrusion, which can create a variety of products with different functions, a mass basis allows those customers using the pultruded product to convert the data to an appropriate functional basis once an equivalency with mass is calculated. Results of the LCI are then expressed in terms of the following functional units.

- The functional unit of the LCI data of the VER and polyurethane precursors (MDI and polyol for rigid PUR) used in composites manufacturing is ***1,000 pounds and 1,000 kilograms of output material produced.***
- The functional unit of the LCI data for the pultrusion process (pultrusion) is ***1,000 pounds and 1,000 kilograms of pultruded product.***

System Boundaries

This Life Cycle Inventory quantifies energy and resource use, water consumption, solid waste, and air and waterborne emissions for VER, two polyurethane precursors used within composites manufacturing (MDI and polyether polyol as typically used to produce rigid polyurethane), and for the pultrusion process. Each individual material, as well as the pultrusion process, are modeled as gate-to-gate unit processes. The VER and pultrusion unit process datasets will be provided to the US LCI Database in this format. The polyurethane precursors were placed in the US LCI Database by the American Chemistry Council. Each unit process LCI module includes transportation for the incoming materials. No packaging materials production for incoming materials, nor for the outgoing product have been included. Any packaging sent to landfill by the manufacturing plant is included in the solid waste; if packaging is sent for recycle or reused by the manufacturing plant, these are not included as solid wastes. Transportation of the finished product to a retailer, use of the product by consumers, and end-of-life of the material or pultruded product is not included in the boundaries of the LCA. Cradle-to-gate data for the composites products are provided to illustrate the contribution of the processes to the LCI results for production of the composites products.

Vinyl Ester Resin

The LCI/LCA results shown for the vinyl ester resin have been provided as incoming materials and operations of the VER manufacturing plant. The individual incoming materials are separated out in all inventory and the global warming potential results, while grouped in the remaining impact categories. The results for the individual incoming materials include the raw materials extraction, intermediate chemicals produced, and the manufacture of the incoming material as sent to the VER manufacturing plant. The results for the VER manufacturing plant include only the gate-to-gate production of VER, which includes all fuels (including electricity) used at the plant, the transport of the incoming materials directly to the VER manufacturing operation, and process releases of solid waste, air emissions and waterborne releases within impact categories.

Figure 2 presents a flow diagram for the production of vinyl ester resin. A sources list for each incoming material is shown in Appendix B. The gate-to-gate data collected for the manufacture of VER for this study were only from plants within the U.S. However, U.S. data were not available for all incoming materials; in this case, the ecoinvent database from Europe was used and adapted to US conditions as possible.

Polyurethane Resin Precursors

The LCI/LCA results shown for the MDI and polyether polyol for rigid PUR have been provided only as incoming materials and the manufacturing plant for each material. The results for the individual incoming materials include the raw materials extraction, intermediate chemicals produced, and the manufacture of the incoming material as sent to the PUR precursor manufacturing plant. The results for the MDI or polyol manufacturing plant include only the gate-to-gate production of the precursor stated, which includes all fuels (including electricity) used at the plant, the transport of the incoming materials, and process releases of solid waste, air emissions and waterborne releases within impact categories.

Figure 3 presents a flow diagram for the production of MDI as taken from the ACC Plastics report[3]. All unit process data are taken from the ACC report for MDI and modeled with the 2021 U.S. electricity grid. No data were collected for the manufacture of MDI for this study.

Figure 4 presents a flow diagram for the production of polyether polyol for rigid PUR as taken from the ACC Plastics report[4]. All unit process data are taken from the ACC report for polyether polyol for rigid PUR and modeled with the 2021 U.S. electricity grid. No data were collected for the manufacture of polyether polyol for this study.

[3] Cradle-to-Gate Life Cycle Analysis of Methylene Diphenyl Diisocyanate (MDI). Franklin Associates, a Div. of ERG. Submitted to the Plastics Division of the American Chemistry Council. July, 2022., p. 9.

[4] Cradle-to-Gate Life Cycle Analysis of Polyether Polyol for Rigid Foam Polyurethanes. Franklin Associates, a Div. of ERG. Submitted to the Plastics Division of the American Chemistry Council. January, 2023., p. 10.

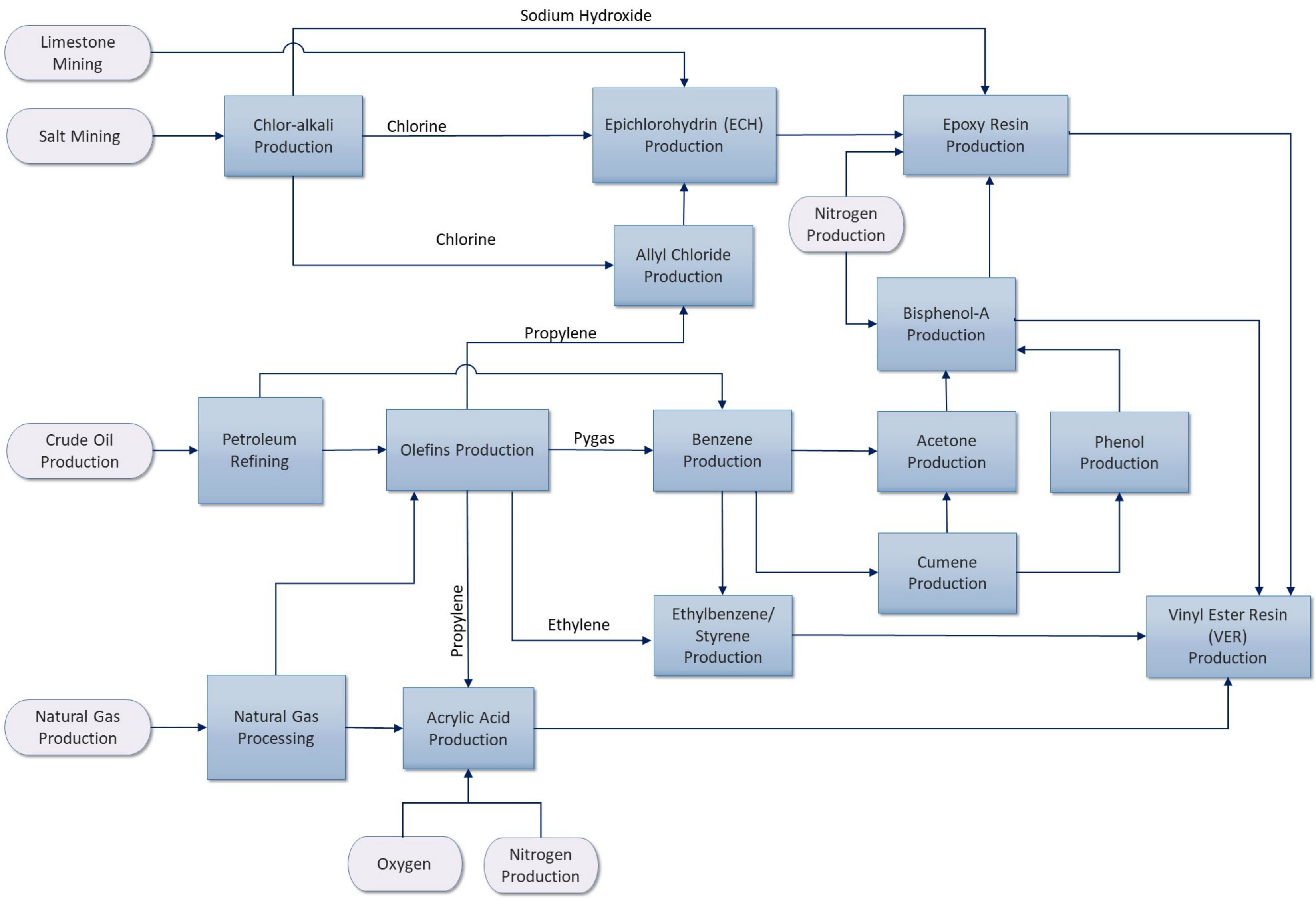


FIGURE 2. FLOW DIAGRAM FOR THE PRODUCTION OF VINYL ESTER RESIN (VER).

Note: Acrylic Acid is a surrogate for Methyl Acrylic Acid.

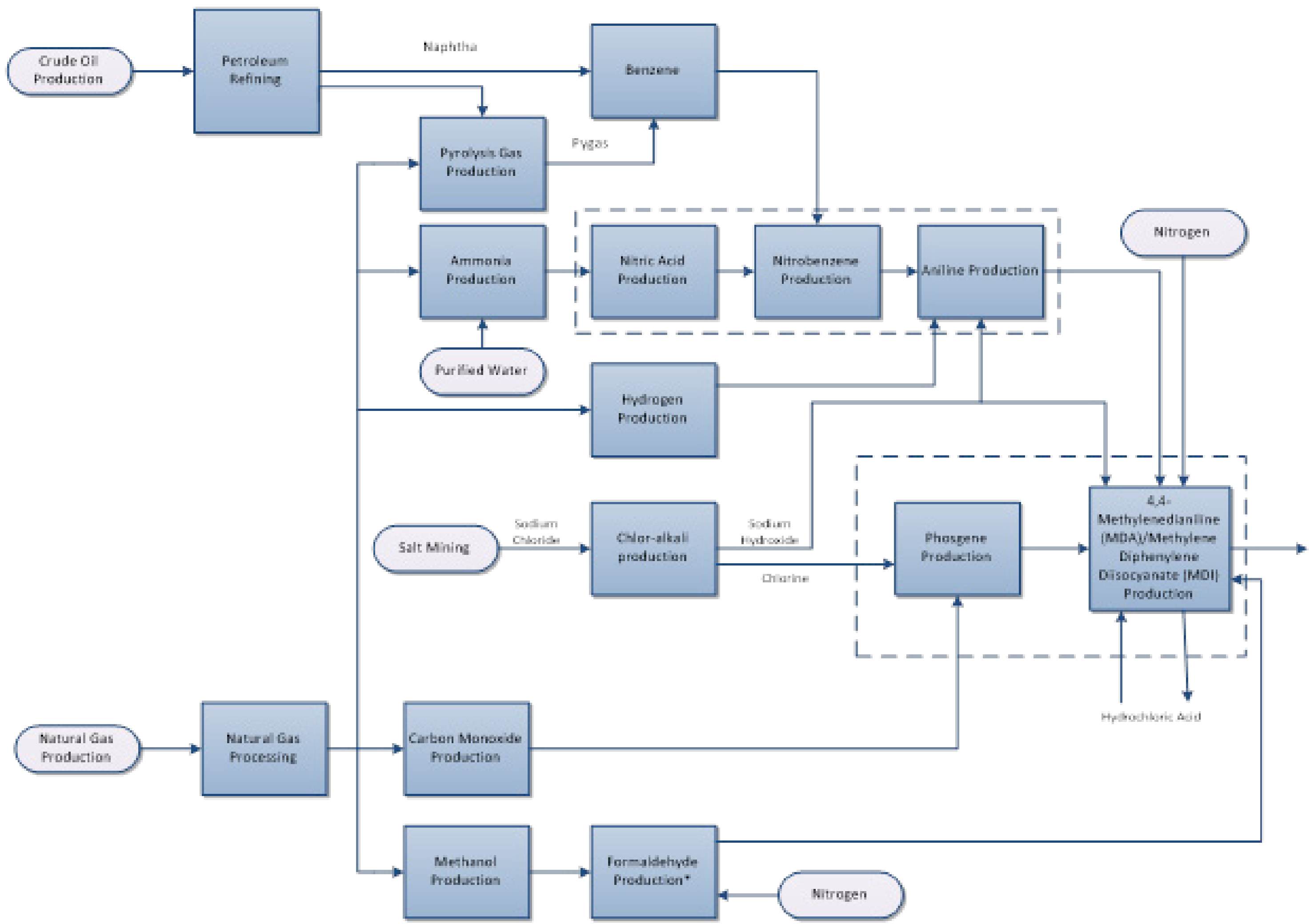
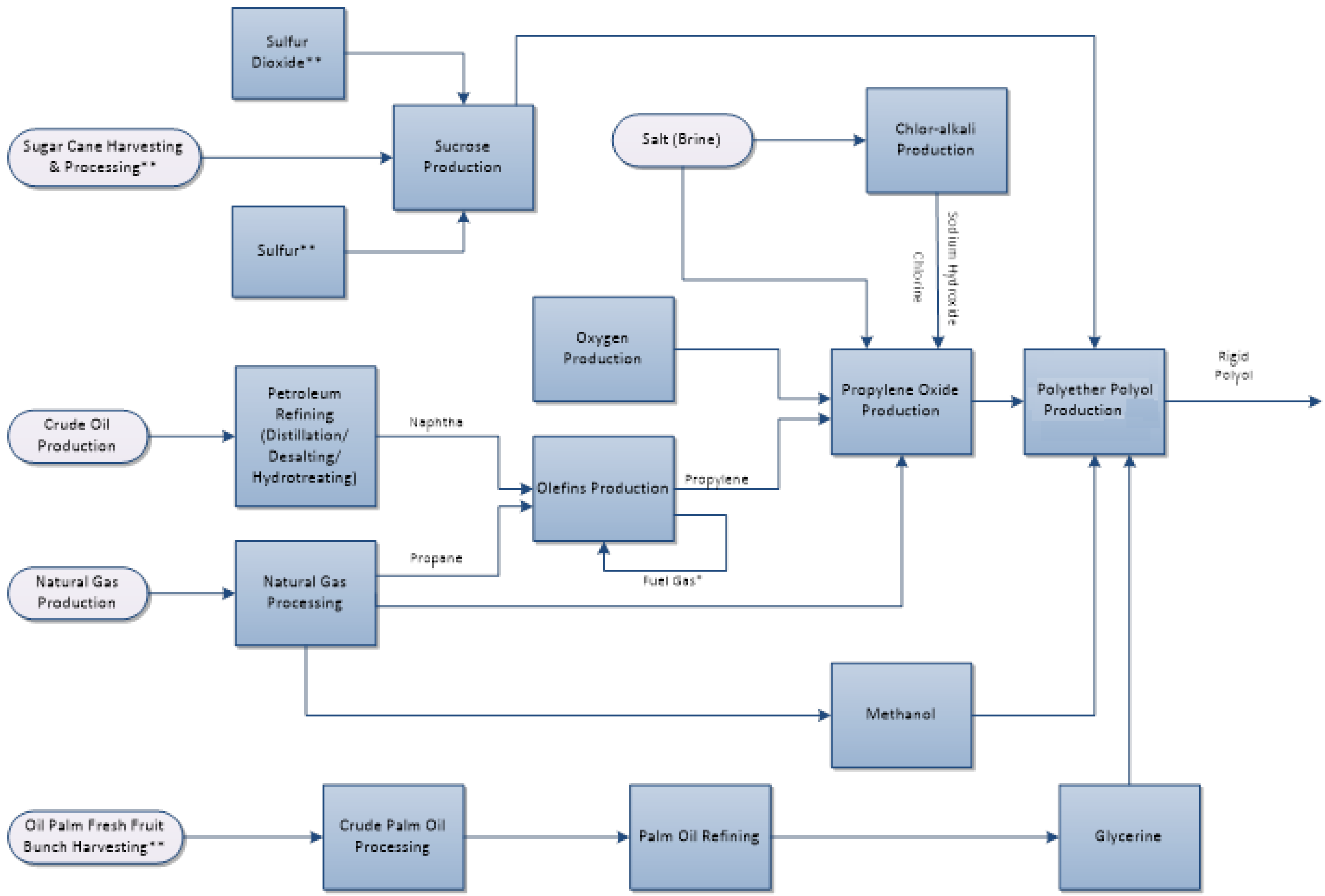


FIGURE 3. FLOW DIAGRAM FOR THE PRODUCTION OF METHYLENE DIPHENYL DIISOCYANATE (MDI).

Note: Nitrogen and sodium chloride data are from ecoinvent and are adapted to U.S. conditions

Note: Dashed lines indicate processes that have been collected together as one dataset or averaged together to conceal confidential data



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

**Some upstream processes such as fertilizers, pesticides, and other inputs are not shown.

FIGURE 4. FLOW DIAGRAM FOR THE PRODUCTION OF POLYETHER POLYOL FOR RIGID POLYURETHANES.

Pultrusion

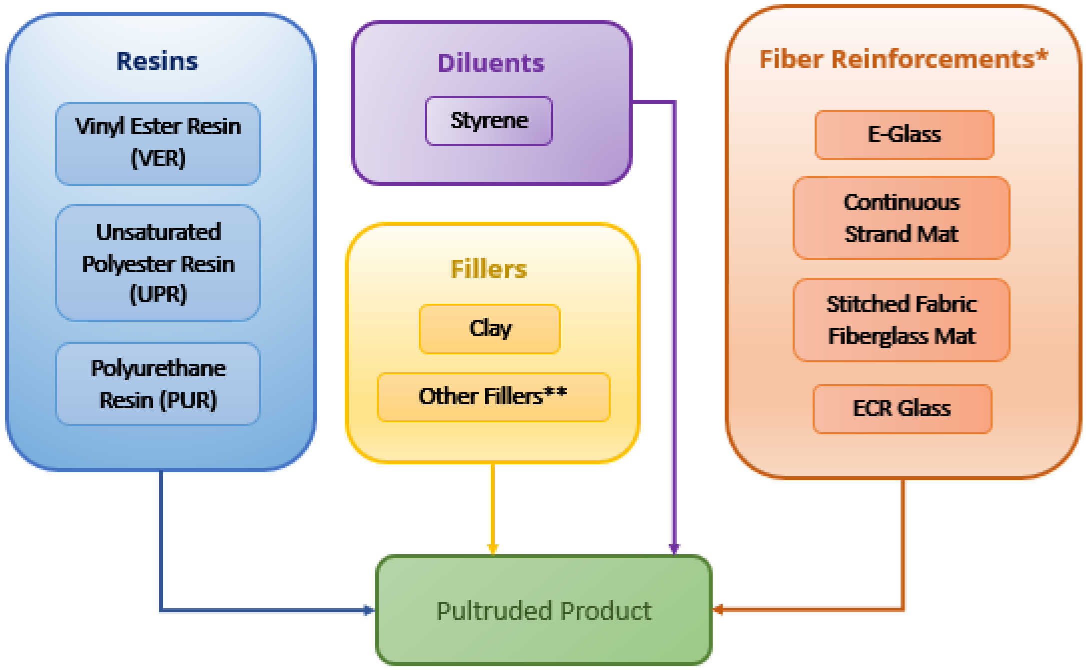
The LCI/LCA results shown for the pultrusion process have been provided as major incoming materials, other materials, and operation of the pultrusion plant. The individual incoming materials are separated out in the inventory and global warming potential results, while grouped in the remaining impact categories. The results for the individual incoming materials include the raw materials extraction, intermediate chemicals produced, and the manufacture of the incoming material as sent to the pultrusion plant. The results for the pultrusion plant include only the gate-to-gate pultrusion process, which includes all fuels (including electricity) used at the plant, the transport of the incoming materials, and process releases of solid waste, air emissions and waterborne releases within impact categories. Different catalysts and initiators were reported, but not included as they were smaller than the 1% of the output cut-off. ***Note that various materials can be used to create a composite product using pultrusion. The inputs for pultrusion in this study are an average of the plants that provided data. No one pultrusion plant would make a specific product using all of the materials shown.***

Figure 5 presents a simplified flow diagram for the pultrusion process. A sources list for each incoming material is shown in Appendix B. U.S. data were collected only for the VER resin and pultrusion process for this study. Some incoming material datasets were not available from U.S. sources; in this case, the ecoinvent database from Europe was used and adapted to US conditions as possible.

Technological Scope

The overall technology is similar in all plants of this analysis for producing VER, MDI, and polyether polyol. The data collection methods for VER, MDI, and polyether polyol include direct measurements, information provided by purchasing and utility records, and engineering estimates. The pultrusion process plants differ in size, the number and variety of inputs used, and the number and variety of products made. This is not a focused study on any particular type of pultrusion plant, but is rather an average of the plants for which information was provided for this analysis.

Vinyl ester resin is produced by the esterification of an epoxy resin with unsaturated monocarboxylic acids, such as acrylic or methacrylic acid. The esterification reaction produces a vinyl ester monomer, which then undergoes polymerization. Styrene is the most common reactive diluent used in VER production. Catalysts and inhibitors are also used in the production of VER.



*E-Glass was used as a surrogate for various mat and fiber components
** Filler materials reported by individual companies were not included in the model if the average was not greater than 1% of the output
NOTE: Diluents are not required for all pultruded products.

FIGURE 5. FLOW DIAGRAM FOR THE PULTRUSION PROCESS OF AN AVERAGE PRODUCT

Methylene diphenyl diisocyanate is manufactured by first producing intermediate products; diamines (MDA) and phosgene. Diamines are produced from aniline and formaldehyde reactions and phosgene is produced from carbon monoxide and chlorine gases. The intermediate products are then reacted to form a mixture of several MDI isomers. Purification of crude MDI is the final step in MDI manufacture.[5]

The technology used to manufacture the polyether polyol used in rigid polyurethane production begins with the introduction of a potassium hydroxide catalyst to an initiator. In this analysis, sucrose was chosen as the initiator; however, glycerine and sorbitol are also common initiators used to produce polyether polyols for rigid polyurethane. This solution is then reacted with propylene oxide to form an intermediate. The catalyst is removed using an acid, which produces a salt that must be filtered. This acid amount is small and considered negligible in this analysis. Finally, the polyol is purified of side products and water through distillation.[6]

[5] Cradle-to-Gate Life Cycle Analysis of Methylene Diphenyl Diisocyanate (MDI). Franklin Associates, a Div. of ERG. Submitted to the Plastics Division of the American Chemistry Council. July, 2022., p. 10.

[6] Cradle-to-Gate Life Cycle Analysis of Polyether Polyol for Rigid Foam Polyurethanes. Franklin Associates, a Div. of ERG. Submitted to the Plastics Division of the American Chemistry Council. January, 2023., p. 10.

For the pultrusion process, reinforcement fibers are impregnated (coated) with liquid resin by pulling the fibers through a dip tank filled with the resin. Clay may be added to the mixture to improve the strength and thermal stability of the resin. The coated fibers are then formed to the desired shape and pulled through a heated die to cure the fiber-reinforced resin. The composite product exits the die as a continuous profile with the desired-cross sectional shape. As stated previously, the differences in input materials and output products may affect the amount of energy required and types of emissions that are produced during this process; however, the pultrusion technology is the same.

Temporal and Geographic Coverage

For the primary data collected (VER and pultrusion), each producer was requested to provide data for a one year period that best represented their average production within a 2 year window (2021 through 2022). This was done as some companies were still ramping up from COVID issues that affected their business, while others had little or no production issues during COVID. Three of the four VER producers chose 2021 to represent their data, while one company chose a partial year in 2021 with the remainder in 2022. Two of the four pultrusion processors chose 2021 to represent their data, while one chose 2022, and one company chose a partial year in 2021 with the remainder in 2022. Each individual company reviewed their data in comparison to the average and verified their data were representative of an average year for VER production or the pultrusion process at their company.

According to the ACC's reports, for the MDI and polyether polyol primary data collected, companies were requested to provide data for 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. For MDI, three companies provided data for the year 2015, and one company provided data for the year 2017. For polyether polyol, one plant provided data for the year 2015, and one plant provided data for the year 2017, which was considered an average year for that company. After reviewing individual company data in comparison to the average, each manufacturer verified their data were representative of an average year for MDI production at their company.[7,8]

The geographic scope of this study is composites manufacturing processes in North America; however, data were only collected from the U.S. for VER, MDI and the polyol production and from the U.S. and Canada for the pultrusion process. The analysis does include raw materials

[7] Cradle-to-Gate Life Cycle Analysis of Methylene Diphenyl Diisocyanate (MDI). Franklin Associates, a Div. of ERG. Submitted to the Plastics Division of the American Chemistry Council. July, 2022., p. 10.

[8] Cradle-to-Gate Life Cycle Analysis of Polyether Polyol for Rigid Foam Polyurethanes. Franklin Associates, a Div. of ERG. Submitted to the Plastics Division of the American Chemistry Council. January, 2023., p. 10.

sourced from other regions of the world (this primarily applies to crude oil imports and a few material inputs). The main sources of data and information for geography-dependent process (e.g., energy production) are drawn from US specific sources. All datasets from ecoinvent were adapted to U.S. conditions to the extent possible (e.g., by using U.S. average electricity grid and transport mode data). The electricity grid used for this analysis was a mix of US and Canada for 2021, which was the most recent year available. The US and Canadian electricity grids were calculated for 2021 from information provided by the International Energy Agency (IEA).

Exclusions from the Scope

The following components of each system are not included in this LCI study:

1. **Miscellaneous Materials and Additives:** Selected materials such as catalysts (initiators), pigments, inhibitors, 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 VER, MDI, and polyether polyol production are not expected to be understated by any significant amount due to substances that may be used in small amounts.

2. **Capital Equipment:** The materials and energy inputs as well as waste outputs associated with the manufacture of capital equipment are excluded from this analysis. This includes equipment to manufacture buildings, motor vehicles, and industrial machinery. In general, these types of capital equipment are used to produce large quantities of product output over a useful life of many years. Thus, energy and emissions associated with the production of these facilities and equipment generally become negligible.

3. **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. Energy requirements and related emissions are assumed to be quite small for support personnel activities.

4. **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 three systems analyzed in this report.

Cut-Off Criteria

This LCI elects to use the one percent by mass cut-off criteria. In other words, any material flow comprising less than one percent by weight of the system is excluded. This cut-off assumption is based on past LCI studies that demonstrate that materials which comprise less than one percent of system weight have a negligible effect on total LCI results. The exception to this criterion is that if a material less than one percent by mass of the system is hazardous, toxic, and/or produces environmental burdens in excess of its weight fraction of the finished product; in this case, the material should be included in the LCI. Quite a few additives within this inventory have been excluded due to being less than 1 percent of the product. It was determined that these additives, if summed, are less than 5 percent total of the product system as required by ISO 14044. It should be noted that if data were readily available for components that comprise less than one percent of a system's weight, these components have been included in the analysis.

INVENTORY AND IMPACT ASSESSMENT RESULTS CATEGORIES

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

The LCI and LCIA results categories and methods applied in this study are displayed in Table 1. This study addresses global, regional, and local impact categories. For most of the impact categories examined, the TRACI 2.1 method, developed by the United States Environmental Protection Agency (EPA) specific to U.S. conditions and updated in 2012, is employed.[9] In addition, the following LCI and LCIA categories included in the results reported in the analysis are described below:

[9] 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.

- **Energy demand:** This method is a cumulative inventory of all forms of energy used for processing energy, transportation energy, and feedstock energy. This analysis reports the total energy demand, which is used as an indicator of overall consumption of resources with energy value; plus, the renewable and non-renewable energy demand are reported separately to assess consumption of fuel resources that can be depleted. Energy is also categorized by individual fuel types, as well as by process/fuel vs. feedstock energy.
- **Total solid waste:** Solid waste is assessed as a sum of the inventory values associated with this category. Solid waste for this analysis only include process wastes and fuel-related wastes; no postconsumer solid wastes have been included as end-of-life is outside the boundaries of the scope. Solid wastes from fuel combustion (e.g., ash) are assumed to be landfilled. This category is also broken into hazardous and non-hazardous wastes and their end-of-life (e.g., incineration, waste-to-energy, or landfill). This category does not include solid wastes that are sold for use or reuse or solid wastes sent for recycle.
- **Water Consumption:** 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. 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. 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.

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
	Photochemical ozone creation potential (Smog formation)	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 O_3 eq and kg O_3 eq	TRACI v2.1

- **Global Warming Potential:** The 100-year global warming potential (GWP) factors for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2013[10] are: fossil carbon dioxide 1, fossil methane 28, and nitrous oxide 265. The GWP factor for a substance represents the relative global warming contribution of a pound of that substance compared to a pound of carbon dioxide. The weights of each greenhouse gas are multiplied by its GWP factor to arrive at the total GWP results. Although normally GWP results are closely related to the energy results, the feedstock energy is not associated with GWP due to the sequestration of the feedstock material within a material such as plastic.
- **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 (AP) 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 NOx and SO2, as a function of the location of the emission.[11,12]
- **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.[13] The TRACI characterization factors for eutrophication are the product of a nutrient factor and a transport factor.[14] 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 (NOx) 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.
- **Ozone Depletion Potential (ODP)**: Stratospheric ozone depletion (ODP) is the reduction of the protective ozone within the stratosphere caused by emissions of

[10] 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.

[11] 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.

[12] 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.

[13] 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.

[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.

ozone-depleting substance (e.g., CFCs and halons). The ozone depletion impact category characterizes the potential to destroy ozone based on a chemical's reactivity and lifetime. Effects related to ozone depletion can include skin cancer, cataracts, material damage, immune system suppression, crop damage, and other plant and animal effects. Some of the main sources of emissions contributing to ODP are minute amounts of tetrachloromethane, HCFCs, and halons, which are emitted during the extraction of petroleum, used as fuel and material for many chemicals produced.

- **Photochemical Ozone Creation Potential (POCP) or 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 NOx and volatile organic compounds (VOCs), resulting in tropospheric (ground-level) ozone and particulate matter. Endpoints of such smog creation can include increased human mortality, asthma, and deleterious effects on plant growth.[13] 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.

DATA SOURCES

The purpose of this study is to develop a life cycle profile for VER, PUR precursors, and the pultrusion process using the most recent data available for each process. Unit process LCI data for VER and pultrusion were collected for this study from producers for the year 2021-2022. Plants were given a 2 year range to choose one year that best represented an average year for their plant. Then, weighted averages using production amounts were calculated from the plant data collected.

LCI data for the production of VER were collected from four producers (five plants) within the United States. Three of the four companies provided data specifically for 2022, while one company provided data for a continuous year starting in 2021 and completing in 2022. The only coproduct included for some companies was minute amounts of downgraded product sold separately. For incoming materials, US data were used where possible, but in some cases, ecoinvent (a European database) data were adapted to US conditions. This adaptation includes the electricity grid, transportation modes/miles, and at times a change of fuel type (e.g., coal is not commonly used in boilers onsite, which would be changed to the equivalent energy using natural gas).

LCI data for the pultrusion process were collected from four processors (four plants) within the United States and Canada. Two of the four companies provided data specifically for 2022, while one company provided data from 2021, and one company provided data for a continuous year starting in 2021 and completing in 2022. The data included all products pultruded at the plant. For incoming materials, US data were used where possible, but in some cases, ecoinvent (a European database) data were adapted to US conditions as discussed previously in this section.

As ACC included polyurethane precursors in their plastics database, the latest version of MDI and polyether polyol for rigid PUR was included in this report using information and unit process data from those ACC reports. Because the polyol average data only had two data providers, no unit process data were available for this report. Average unit process LCI data for MDI and polyol were calculated using data collected for the years 2015 and 2017. Some LCI data for the intermediate chemical inputs to the precursors were also collected for that timeframe. More information on these unit processes can be found in the ACC LCA reports for MDI and polyether polyol for rigid PUR on the ACC website.

For background data (raw material and intermediate chemicals) used to develop cradle-to-gate environmental profiles of VER and the pultrusion process, data from a number of published sources were utilized for this report. The data sources used to characterize upstream processes associated with VER and pultrusion are listed in Tables 48 and 49 in Appendix B of this report. For the polyurethan precursors, the same sources were used for all background data as were used for the ACC study with the exception of the electricity grid, which was updated to 2021.

DATA COLLECTION/VERIFICATION

The process of gathering data is an iterative one. The included data providers were contacted by ACMA and agreed to participate in this inventory by collecting unit process data at their plant(s). Data collection sheets that were developed specifically for VER and the pultrusion process were provided to assist in gathering the necessary LCI data. Upon receipt of the completed worksheets, the data were evaluated for completeness and reviewed. Data suppliers were then sent questions about the data sent, including discussions on the process technology, waste treatment, coproducts, and any assumptions necessary to understand the data and boundaries. Once all questions were answered and each dataset was completed and verified, the datasets for the VER or the pultrusion process were aggregated into a single set of data by weighting the facility's data by its plant production amount percentage. In this way, a representative set of data can be estimated from a limited number of data sources. The individual company's VER or pultrusion dataset were then documented and returned side by side with the averaged dataset to each data supplier for their review. This was done to allow the companies to ask questions about the average, as well as see that no data points within their data were compromised within the average.

Franklin Associates takes care to protect data that is considered confidential by individual data providers. In order to protect confidential data sets provided by individual material or processing facilities, only weighted average data sets can be shown for each type of facility.

DATA QUALITY ASSESSMENT

ISO standard 14044:2006 states that "Data quality requirements shall be specified to enable the goal and scope of the LCA to be met." The data quality requirements listed include time-related representativeness, reproducibility, completeness, and more. The quality of individual data sets varies in terms of representativeness, measured values or estimates, etc.; however, all process data sets used in this study were thoroughly reviewed for accuracy and currency and updated to the best of our capabilities for this analysis. Environmental profiles presented in this report for the VER production and pultrusion process were developed using the data provided by participating companies for this study.

The data quality goals for this analysis were to use data that are (1) geographically representative for the VER, PUR precursors and pultrusion based on the locations where material sourcing and production take place, and (2) representative of current industry practices in these regions. As described in the previous section, four companies each provided current, geographically representative data for all primary VER and Pultrusion data collected for this LCA. The PUR precursor LCI data were from 2015-2017 but were the newest data available for the United States and Canada. ACC is planning to update these datasets within the next two years.

The incoming material and fuel datasets for the VER, PUR precursors, and pultrusion process 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[15,16]. 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 incoming material data sets used were the most current and most geographically and technologically relevant data sets available during the data collection phase of the project.

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

[15] Argonne National Laboratory, Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies Model; Energy Systems Division, https://greet.es.anl.gov/, 2017, accessed August 1, 2018.

[16] 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].

aggregated averaged datasets were also reviewed by the providing companies as compared to the provided dataset. Companies were requested to review whether their data were complete and to comment about their or the average dataset.

Representativeness: VER manufactured in the United States and Canada is representative of the majority of VER producers within the United States. The four companies provided data from their facilities using a very similar technology with differences normally including the type and amount of catalysts, inhibitors and other additives. After reviewing individual company data in comparison to the average, each manufacturer verified the average data from 2021-2022 was a representative for VER production in the U.S and Canada at that time.

The pultrusion process is representative of a range of pultrusion plants across the U.S. and Canada. Due to different products made (e.g., rebar, utility poles, structural products, and decking products) and plant sizes, differences in input materials, energy and emissions were seen in the LCI data collected. However, as this unit process was to be representative of a wide range of product types that are pultruded, the differences in plant data were deemed acceptable to create an aggregated representative dataset. Each company now has available the LCI unit process data that they provided for this analysis and could present their own individual plant or even produce LCA results specific to their products.

The LCI data for the Epoxy and BPA inputs came from the ecoinvent database from Europe but were adapted to U.S. conditions and were linked to intermediate chemicals LCI data from the ACC plastics database. ACC collected primary data from olefins manufacturers from the year 2015, which was used as an intermediate chemical for many of the input materials.

Average U.S. statistics were used for refined petroleum products and processed natural gas to develop much of the intermediate chemical 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 VER and pultrusion unit process data were based on the best available data at the time the study was conducted. As in all LCA studies, the ability to develop a representative average is determined by the number of companies willing to participate. Data from this analysis was used to develop the most representative average for VER production and pultrusion process in the 2021-2022 time frame 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 were taken from private databases and could not be provided due to confidentiality.

The unit process data for each individual material or process are shown in the results chapter and sources are provided for each material input in Appendix B. The PUR precursors refer back to the ACC report for discussions of incoming materials.

Objectivity: Each unit process in the life cycle study is researched independently of all other processes. No calculations are performed to link processes together with the production of their raw materials until after data gathering and review are complete. This allows objective review of individual data sets before their contribution to the overall life cycle results has been determined. Also, because these data are reviewed individually, assumptions are reviewed based on their relevance to the process rather than their effect on the overall outcome of the study.

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

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 VER and the pultrusion process for this analysis, as well as MDI/MDA, polyether polyol, aniline, chlor-alkali, and steam cracking of the olefins from recent ACC studies on the PUR precursors. All data received were carefully evaluated before compiling the production-weighted average data sets used to generate results. Supporting background data were drawn from credible, widely used databases including the US LCI database, GREET, and ecoinvent.

It should be noted that a report from the International Energy Agency (IEA) that at this time has not been subject to validation through a scientific peer review suggests that unwanted methane emissions during oil and gas extraction, processing and transport are higher than assumed in current LCA databases. The IEA has created a methane tracker website reporting these additional methane emissions[17]. As a base case, the present U.S. cradle-to-gate reports use oil and gas extraction information published by the National Energy Technology Laboratory (NETL), Argonne National Laboratory (ANL), and the Energy Information Administration (EIA), which currently do not include these increased methane losses.

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. LCI practitioners vary to some extent in their approaches to these issues. The following sections describe the approach to each issue used in this study.

The methodology issues stated here are specific to the VER, PUR precursors, and pultrusion process. To access methods used for some of the intermediate chemicals, such as the olefins produced at the stream crackers, the source documents should be examined. Some sections pertaining specifically to the MDI and polyether polyol have been taken from the original ACC reports on these precursors and are footnoted as such.

Allocation Procedures

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

[17] IEA (2020), Methane Tracker 2020, IEA, Paris https://www.iea.org/reports/methane-tracker-2020

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

Environmental burdens are allocated among the coproducts when raw materials and emissions cannot be directly attributed to one of several product outputs from a system. It has long been recognized that the practice of allocating the environmental burdens among the coproducts is less desirable than being able to identify which inputs lead to specific outputs. In this study, co-product allocations are necessary because of multiple useful outputs from the "upstream" chemical process involved in producing MDI, as well as upstream materials chlorine/sodium hydroxide and olefins. The VER and polyether polyol only have small amounts of off-spec or lower quality material as a coproduct on a limited number of plants. Although the pultrusion plant has a number of different products produced, no one specific product is stated as the output, so no allocation has been made to each product. Instead, all products from the pultrusion process are considered one output. Coproducts are allocated on an individual plant basis prior to the averaging of the LCI data.

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

Elemental/Mass Coproduct Allocation and Rationale for its Use for MDI

In 2021, the European Diisocyanate and Polyol Producers Association (ISOPA) released their updated TDI/MDI Ecoprofile, which used an allocation method combining elemental and mass allocation for the production of the isocyanate and its coproduct, hydrochloric acid. The ACC had originally used mass for the allocation method and decided to continue to use the mass allocation for the 2022 report results but have discussed using the elemental + mass allocation in future updates. The ACC provided results for both allocation methods in a sensitivity analysis section of the MDI report. As it is likely that the ACC will change methods to the elemental and mass method in the coming update, the ISOPA method has been used for MDI allocation in this report.

For the ACMA analysis, the elemental + mass allocation method has been applied to the MDI data. For this allocation type, the following allocations are given using the elemental + mass allocation:

- The chlorine input is fully allocated to the production of HCl.
- The inputs used to create MDA and Phosgene only are allocated fully to MDI.
- Chlorine or Hydrochloric acid atmospheric emissions or waterborne releases are fully allocated to the HCl.
- All other inputs/outputs have been given mass allocation[18].

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. If system expansion is not possible, 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 many of the intermediate chemical process steps in this analysis. The material coproducts from olefins production for all plants included propylene, ethylene, butadiene, pyrolysis gas, ethane, hydrogen, acetylene, crude benzene, and small amounts of various heavy end products. In the chlor-alkali plant, allocations have been made to focus on which product the inputs or outputs associate within the process. The specifics of the allocations given in the chlor-alkali plants are detailed in the ACC report, Cradle-to-gate Life Cycle Analysis of Polyvinyl Chloride (PVC) Resin.[19] In some cases, small amounts of off-spec or lower quality materials were considered products and the inputs/outputs of the product/coproduct were allocated on a mass basis. The material coproduct from MDI production includes a sizable amount of hydrochloric acid, which was allocated as discussed in the previous section.

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).

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[18] Cradle-to-Gate Life Cycle Analysis of Methylene Diphenyl Diisocyanate (MDI). Franklin Associates, a Div. of ERG. Submitted to the Plastics Division of the American Chemistry Council. July, 2022., p. 10.

[19] Cradle-to-Gate Life Cycle Analysis of Polyvinyl Chloride (PVC) Resin. Franklin Associates. Submitted to the Plastics Division of the American Chemistry Council. December, 2021.

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

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 for intermediate chemicals 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 the United States and Canada are interlinked. Users of electricity, in general, cannot specify the fuels used to produce their share of the electric power grid; however, they are able to purchase renewable energy shares in some cases. These electricity amounts can be seen in the unit process LCI data as *electricity from renewable sources* as a combination of hydropower, solar, and wind energy. Data for this analysis was collected from plants in the United States and Canada.

Foreground processes in this model took place in either the U.S. or Canada, so electricity was modeled based on IEA average resource mix values for the U.S. and Canada from 2021[20], which was the latest available data at the time of modeling. The combined U.S. and Canadian grid mix was calculated by summing the resource mix GWh values for both countries in 2021 and dividing by the total electricity production. The North American grid mix was not used because it includes Mexico. The electrical grid mixes and their line loss values are listed in Table 2 and are broken down by resource type.

[20] IEA. (2021). Electricity Information. https://www.iea.org/data-and-statistics/data-product/electricity-information

TABLE 2. ELECTRICITY GRID RESOURCE MIX

Resource	IEA U.S. and Canada 2021
Coal	20.4%
Oil	0.80%
Natural gas	34.0%
Nuclear	18.0%
Hydro	13.2%
Biofuels	1.25%
Wind	8.37%
Solar	3.08%
Geothermal	0.37%
Other*	0.44%
Losses^	1.13%

*Includes other fossil and non-fossil sources

^Includes line loss and energy industry use

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.

Energy of Material Resource (also Material Feedstock Energy)

For some raw materials, such as petroleum, natural gas, and coal, the amount consumed in all industrial applications as fuel far exceeds the amount consumed as raw materials (feedstock) for products. The primary use of these materials in the marketplace is for energy. The total amount of these materials can be viewed as an energy pool or reserve. The use of a certain amount of these materials as feedstocks for products, rather than as fuels, removes that amount of material from the energy pool, thereby reducing the amount of energy available for consumption. This use of available energy as feedstock is called the energy of material resource (EMR) and is included in the inventory. The energy of material resource represents the amount the energy pool is reduced by the consumption of fuel materials as raw materials in products and is quantified in energy units.

EMR is the energy content of the fuel materials input as raw materials or feedstocks. EMR assigned to a material is not the energy value of the final product but is the energy value of the raw material at the point of extraction from its natural environment. For fossil fuels, this definition is straightforward. For instance, petroleum is extracted in the form of crude oil. Therefore, the EMR for petroleum is the higher heating value of crude oil.

Once the feedstock is converted to a product, there is energy content that could be recovered, for instance through combustion in a waste-to-energy waste disposal facility. The energy that can be recovered in this manner is always somewhat less than the feedstock energy because the steps to convert from a gas or liquid to a solid material reduce the amount of energy left in the product itself.

In North America, energy content is most often quoted as higher heating value (HHV); this value is determined when the product is burned and the product water formed is condensed. The use of HHV is considered preferable from the perspective of energy efficiency analysis, as it is a better measure of the energy inefficiency of processes.[21] Lower heating values (LHV), or net heating values, measure the heat of combustion when the water formed remains in the gaseous state. The difference between the HHV and the LHV depends on the hydrogen content of the product. As the carbon amount of the combusted material climbs higher, the difference in these two values levels off to approximately 7.5 percent.[22]

ASSUMPTIONS & LIMITATIONS

Although the foreground processes in this analysis were populated with primary data and the background processes come from reliable databases and secondary data, most analyses still have limitations. Further, it is necessary to make a number of assumptions when modeling, which could influence the final results of a study. Key limitations and assumptions of this analysis are described in this section.

Geographic Scope. Data for foreign processes are generally not available. This is usually only a consideration for the production of oil that is obtained from overseas. In cases such as this, the energy requirements and emissions are assumed to be the same as if the materials originated in the United States. Since foreign standards and regulations vary from those of the United States, it is acknowledged that this assumption may introduce some error. Transportation of crude oil used for petroleum fuels and resins is modeled based on the current mix of domestic and imported crude oil used.

Pultrusion Process LCI Data. The LCI average unit process data collected for the pultrusion process represents many different pultruded products. It is not representative of just one type of pultruded product, but the industry as a whole. No single pultruded product requires all the inputs shown in the LCI average data in Chapter 4. Also, the input materials for this process are not limited to those shown in this analysis; for example, phenolic resins are used as a resin within some pultruded products but were not used at the plants providing data for this report. This is a limitation as the results may be higher or lower than that of a specific pultruded product. However, having the LCI data in the U.S. LCI Database does allow those

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21 Worrell, Ernst, Dian Phylipsen, Dan Einstein, and Nathan Martin. (2000). Energy Use and Energy Intensity of the U.S. Chemical Industry. Ernest Orlando Lawrence Berkeley National Laboratory. April, 2000. p. 12.

22 Seddon, Dr. Duncan. (2006). Gas Usage & Value. PennWell Books. p. 76. Figure 4-1.

companies or practitioners that need to include a pultruded product in their LCA to do so. Providing the data as a unit process allows those companies to potentially adapt the dataset if they do know the specific inputs to the pultrusion product they are evaluating.

Use of Ecoinvent data for Epoxy. The LCI data for epoxy were adapted from the Ecoinvent private database. After the LCI models were complete, Argonne National Laboratories released an epoxy dataset to the U.S. LCI Database. This epoxy dataset in the U.S. LCI Database only includes energy and crude oil as inputs. Because of the incomplete nature of the dataset, Franklin decided to continue to use the Ecoinvent data and the models were not changed. If a company or practitioner does not have access to the Ecoinvent database and uses the GREET data as a surrogate, the results will be less as it is missing a number of inputs (i.e., crude oil extraction is used to represent all inputs) as well as emissions for the epoxy unit process and all intermediate chemical processes.

Adaptation of Ecoinvent Datasets. A number of assumptions were made to adapt all Ecoinvent datasets used in this study. These include:

- Transport distances were assumed to be equivalent to U.S. distances, but modes of transport were linked to U.S. data.
- Cooling water and other water shown that were likely not consumed were not included in the Water Consumption method.
- All inputs were changed to U.S. sources as available.
- Energy sources were reviewed for possible differences in the EU and U.S. industry. For example, EU is more likely to use oil type fuels than the U.S.; therefore, where larger amounts of oil-based fuels were used, the energy amount was calculated and converted to natural gas.

Use of MDI and Polyether Polyol from ACC Reports. This report uses the data from the ACC reports on MDI and polyether polyol for rigid PUR. The elemental + mass allocation method was chosen for MDI due to the likelihood that ACC will use it in their update of their plastics database. Because the polyether polyol average data only had two data providers, no unit process LCI data were available for this report. Only the system process LCI data are available in Appendix A. The results for the polyether polyol come from that system LCI dataset.

PRACTICAL APPLICATION OF THE LCI DATA

The unit process tables at the beginning of each subsequent chapter of this report contain gate-to-gate process data for each product system. Appendix A contains cradle-to-gate LCI results for the VER, MDI, polyether polyol, and pultrusion process. These system processes are fully aggregated data sets; that is, they include the burdens for all the processes required to produce the material and energy inputs for the composite materials and pultrusion process. These fully aggregated datasets include not only the direct burdens for the material production or the pultrusion process, but also the upstream burdens for the production and combustion of all fuels used in the processes, as well as the production of all input materials used in the process, and the production and combustion of fuel required to deliver materials used in the process. The advantage of using aggregated data sets is that all the related data have been aggregated into a single data set. However, an important disadvantage of using aggregated data sets is that the contributing data are "locked in" to the aggregated total so that it is generally not possible to directly adjust the total end results to reflect any subsequent changes in any individual contributing data sets (for example, a reduction in natural gas use at the processing step or a change in the mix of fuels used to produce the grid electricity used in the processing step).

When life cycle practitioners construct models for product systems, they normally construct the models by linking unit process data sets (such as the data sets shown for the gate-to-gate product systems in the following chapters), rather than aggregated data sets like much of the data in this report. In unit process modeling, the quantities of material inputs and fuel inputs to each unit process are linked to data sets for the production of those materials and for production and combustion of fuels. This modeling approach is the approach that was used in this analysis to construct the fully aggregated datasets. In the unit process modeling approach, the linked data will automatically adjust for changes in any contributing process or fuel-related dataset. In a full cradle-to-grave composites product LCA, the data sets for the materials used in the product would be combined with the data for the composites processing, use and end-of-life management.

CHAPTER 2. VINYL ESTER RESIN

This chapter describes the production of Vinyl Ester Resin (VER), presents the compiled gate-to-gate unit process LCI data for production of VER, and presents LCI and LCIA results for cradle-to-gate production of 1,000 pounds and 1,000 kilograms of VER.

GATE-TO-GATE LCI DATA FOR PRODUCTION OF VER

VER is a durable thermosetting polymer commonly used in manufacturing composite materials. VER end markets are primarily construction, automotive, pipes, tanks and marine, and are increasingly used for items such as wind energy.[23] For reinforced applications, the function of VER in the composite material is to provide a matrix for structural reinforcements and to distribute and transfer load between the reinforced fibers and adjacent structures. VER is also used in non-reinforced composite applications, such as adhesives. For all applications, VER is selected for use because of its toughness and its resistance to corrosion and shrinking.

Vinyl ester resin is produced by the esterification of an epoxy resin with an unsaturated monocarboxylic acid (UMA). Methacrylic acid is the most common monocarboxylic acid used in VER production. Acrylic acid may also be used to manufacture VER; however, studies have found that VER prepared with methacrylic acid possesses greater thermal stability than this alternative.[24] The epoxy resin and UMA are mixed in a reactor vessel and heated to initiate the esterification reaction and produce the vinyl ester monomer. Styrene is commonly used as a diluent in VER production to achieve the desired viscosity of the mixture. Following this step, a catalyst is added to the mixture and initiates the polymerization reaction between the epoxy groups of the resin and the carboxylic acid groups of the unsaturated acid, resulting in the formation of ester linkages. The reaction is exothermic and releases heat, so cooling systems are often used to maintain the optimal temperature for the reaction.

The final VER product is shipped to composite product manufacturers via drum, tote, or bulk tankers where it is combined with other materials, such as fibers and fillers, and processed into a finished or semi-finished part. The properties of VER depend on the types and proportions of monomers (i.e., acids, epoxy, diluent) reacted.

[23] Tu, R., Sodano, H. (2021). Additive manufacturing of high-performance vinyl ester resin via direct ink writing with UV-thermal dual curing. Accessed from: https://www.sciencedirect.com/science/article/pii/S2214860421003432

[24] Gupta, P., Chandaliya, P., Hiran, B.L. (2012). Synthesis and comparative study of vinyl ester resin prepared by using methyl methacrylate and acrylic acid. Accessed from: https://www.tsijournals.com/articles/synthesis-and-comparative-study-of-vinyl-ester-resin-prepared-by-using-methyl-methacrylate-and-acrylic-acid.pdf

Table 3 presents the complete LCI unit process data for the average industrial production of 1,000 pounds and 1,000 kg of VER. Figure 2 in Chapter 1 provides a flow diagram of all inputs included in the production of VER. Further information on the data sources of these material inputs are shown in Appendix B.

TABLE 3. LCI UNIT PROCESS AVERAGE DATA FOR VER PRODUCTION

	English units 1,000 lb		SI Units 1,000 kg		
Material Inputs					
Epoxy Resin	428	lb	428	kg	
Bisphenol A	78.8	lb	78.8	kg	
Styrene	364	lb	364	kg	
Methylacrylic Acid	129	lb	129	kg	
Glass Sand (Silica)	4.7	lb	4.7	kg	
Energy					
Process Energy					
Electricity from grid	85.3	kWh	188	kWh	
Electricity from Renewable Sources	3.2	kWh	7.0	kWh	
Natural Gas	865	ft^3	54.0	m^3	
Transportation Energy					
Ocean freighter	919	ton·mi	2,960	tonne·km	
Truck	150	ton·mi	483	tonne·km	
Rail	253	ton·mi	813	tonne·km	
	1,000 lb		1,000 kg		
Environmental Emissions					
Atmospheric Emissions					
VOC, unspecified origin	0.10	lb	0.10	kg	*
Particulates, unspecified	0.17	lb	0.17	kg	
Methylmethacrylate (MMA)	1.0E-03	lb	1.0E-03	kg	*
Waterborne Releases (none)					
Solid Wastes					
Solid Waste, process to landfill	4.4	lb	4.4	kg	
Solid Waste Sold for Recycling or Reuse	1.7	lb	1.7	kg	
Solid Waste, process to incineration	0.16	lb	0.16	kg	
Solid Waste, process to waste-to-energy incineration	0.64	lb	0.64	kg	
Hazardous waste to incineration	0.020	lb	0.020	kg	
Hazardous waste to waste-to-energy incineration	2.3	lb	2.3	kg	
Water Consumption	0.010	gal	0.083	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, 2022

LIFE CYCLE INVENTORY AND IMPACT ASSESSMENT RESULTS FOR VER

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

Life cycle inventory results:

- Energy demand
  - Cumulative 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

A description of each of the LCI and LCIA categories can be found in Chapter 1.

Throughout the results sections, the tables and figures break out system results into the following unit processes, for VER:

- Cradle-to-incoming materials – includes the raw materials through the production of the incoming materials.
- VER production – is the gate-to-gate unit process and includes the production of fuels used in the process and transportation of the incoming materials to the production facility.

Some tables and figures include result details for each of the individual input material systems. This split was provided for the main inventory categories, as well as the global warming potential.

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

Energy Demand

Energy Demand has been detailed by renewable and non-renewable energy, as well as by fuel type. A short discussion is provided about the energy of material resource results, which is explained in Chapter 1, as compared to the fuel and process energy results.

Cumulative Energy Demand

Cumulative energy demand results include all renewable and non-renewable energy sources used for process and fuel energy, as well as energy of material resource (also called 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 most of the incoming chemicals (e.g., the energy content of oil and gas used as material feedstocks) to the VER, which is discussed in Chapter 1.

The total energy required to produce vinyl ester resin is 39.4 million Btu per 1,000 pounds of VER or 91.6 GJ per 1,000 kilograms of VER. Table 4 and Figure 6 show total energy demand for the VER system. The VER production energy has been split out from the energy required for incoming materials. Only 6 percent of the total energy is required to produce VER at the plant. The remaining 94 percent is associated with the manufacture of VER input materials.

Table 4 also provides details about the non-renewable and renewable energy use within the total energy. 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), as well as use of uranium to generate the share of nuclear energy in the average U.S. kWh. For the VER system, over 98 percent of the total energy comes from non-renewable sources. The renewable energy (1.57 GJ/1000 kg) used in the VER system comes from a mix of hydropower, wind, and other renewable sources (geothermal, solar, etc.) from electricity production.

In Table 5, a breakout of the percentage of total energy is provided by individual input materials as well as the VER production. When considering the individual VER input materials, greater amounts of epoxy resin and styrene are used in the VER production. This coincides with these materials having the highest energy demand, making up 44 percent and 34 percent of the total energy demand of VER input materials, respectively. The BPA and methylacrylic acid make up less than 10 percent of the total energy each, while the energy of the small additive amounts are less than 1 percent.

TABLE 4. TOTAL ENERGY DEMAND FOR VER SYSTEM

	Total Energy	Non-Renewable Energy	Renewable Energy
	Basis: 1,000 pounds		
	MM Btu	***MM Btu***	***MM Btu***
Cradle-to-incoming materials	37.0	36.4	0.57
Vinyl Ester Resin Manufacture	2.39	2.28	0.10
Total	**39.4**	**38.7**	**0.67**
	Basis: 1,000 kilograms		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	GJ	***GJ***	***GJ***
Cradle-to-incoming materials	86.1	84.7	1.33
Vinyl Ester Resin Manufacture	5.55	5.31	0.24
Total	**91.6**	**90.1**	**1.57**
	Percentage		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	%	***%***	***%***
Cradle-to-incoming materials	94%	92%	1.45%
Vinyl Ester Resin Manufacture	6%	5.8%	0.26%
Total	**100%**	**98%**	**1.71%**

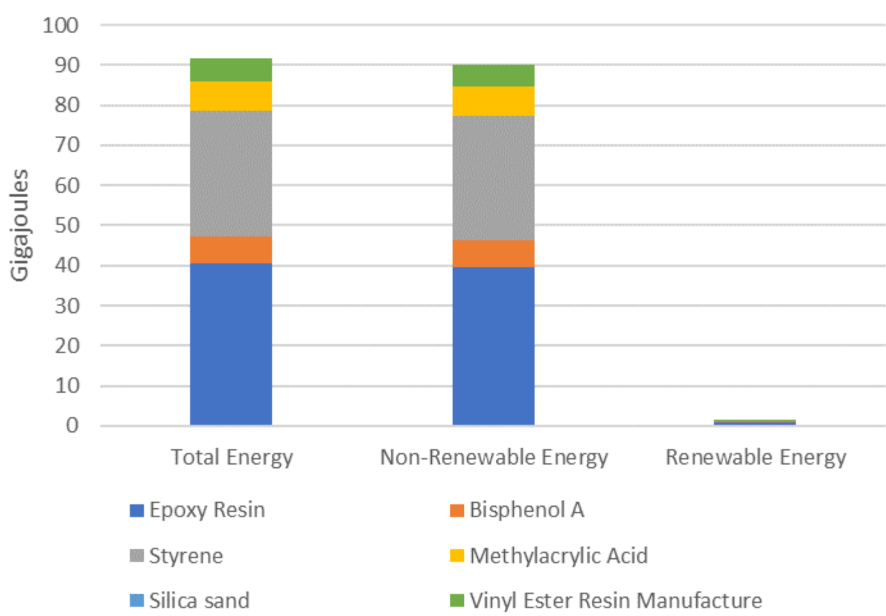

FIGURE 6. TOTAL ENERGY DEMAND BY INCOMING MATERIAL AND VER PRODUCTION

TABLE 5. PERCENT OF TOTAL ENERGY DEMAND BREAKOUT BY MATERIAL AND PROCESS DETAIL

	Energy		
	Total Energy	Non-Renewable Energy	Renewable Energy
	%	%	%
Incoming Materials Total	**94%**	**94%**	**85%**
Epoxy Resin	*44%*	*44%*	*64%*
Bisphenol A	*8%*	*8%*	*8%*
Styrene	*34%*	*35%*	*8%*
Methylacrylic Acid	*8%*	*8%*	*4%*
Silica sand	*0%*	*0%*	*0%*
Vinyl Ester Resin Manufacture	**6%**	**6%**	**15%**
Fuel use onsite	*2%*	*2%*	*0%*
Electricity	*2%*	*2%*	*15%*
Incoming Material Transport	*2%*	*2%*	*0%*
Total	**100%**	**100%**	**100%**

Table 5 also provides a breakout of energy used at the VER plant. These energy amounts are split somewhat evenly among the fuels combusted onsite, the electricity use, and the transport of the incoming materials. The unit process LCI table shows the average amounts used for each of these categories in the breakout. As for all materials shown, the renewable energy is coming from the production of electricity using the renewable fuels shown in Table 2 of Chapter 1. The VER manufacture does include some electricity specifically coming from renewable sources, which is why the percentage from this process for renewable energy is higher.

The energy representing natural gas and petroleum used as raw material inputs for the production of incoming chemicals used to produce VER are included in the cradle-to-incoming material amounts in Table 4. The energy inherent in these raw materials is called the energy of material resource or material feedstock energy as discussed in Chapter 1. Of the total energy (91.6 GJ) for 1,000 kg of VER, 44.5 GJ is material feedstock energy. As shown in Figure 7, approximately 51 percent of the total energy is inherent energy in the natural gas and petroleum used as a feedstock to create chemicals such as olefins, which in turn are used to create intermediate chemicals as material inputs to VER. Of the feedstock sources for VER, an estimated 57 percent come from natural gas, while 43 percent of the feedstock sources come from oil.

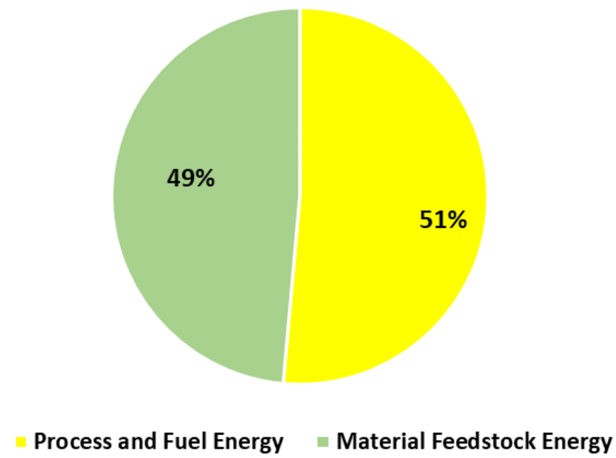

FIGURE 7. PROCESS/FUEL AND MATERIAL FEEDSTOCK PERCENTAGES FOR VER

Energy Demand by Fuel Type

The total energy demand by fuel type for VER is shown in Table 6, as well as the percentage mix in Figure 8. Natural gas and petroleum together make up 90 percent of the total energy used. As can be seen in Figure 7, this is partially due to the material feedstock energy used to create the incoming materials to VER. These material feedstock fuels are part of the energy shown in the natural gas and petroleum split out for cradle-to-incoming materials. The gate-to-gate production energy for vinyl ester resin in the following table and figure represents the energy required for transportation of raw materials to the plant, the energy required to produce the output, and the production of the fuels needed to manufacture the VER.

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 VER production shown in Table 6 and Figure 8, 65 percent of the energy used (59.9 GJ/91.6 GJ) is from natural gas. The greatest amounts of natural gas come from the production of the epoxy and the styrene systems, which do include the natural gas feedstock energy. At the VER plant, 54 percent of the energy used (3 GJ/5.55 GJ) comes from natural gas. Of that natural gas used at the VER plant, 71 percent is combusted on-site, while 26 percent is required to create electricity through the grid.

TABLE 6. ENERGY DEMAND BY FUEL TYPE FOR VER SYSTEM

	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	37.0	24.5	9.28	1.50	1.20	0.29	0.29
Vinyl Ester Resin Manufacture	2.39	1.29	0.60	0.20	0.19	0.05	0.06
Total	**39.4**	**25.7**	**9.88**	**1.71**	**1.39**	**0.33**	**0.35**
	Basis: 1,000 kilograms						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	GJ	*GJ*	*GJ*	*GJ*	*GJ*	*GJ*	*GJ*
Cradle-to-Incoming Materials	86.1	56.9	21.6	3.50	2.79	0.67	0.67
Vinyl Ester Resin Manufacture	5.55	3.00	1.40	0.47	0.44	0.11	0.13
Total	**91.6**	**59.9**	**23.0**	**3.97**	**3.23**	**0.77**	**0.81**
	Percentage of Total						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	%	*%*	*%*	*%*	*%*	*%*	*%*
Cradle-to-Incoming Materials	93.9%	62.1%	23.6%	3.8%	3.0%	0.7%	0.74%
Vinyl Ester Resin Manufacture	6.1%	3.3%	1.5%	0.5%	0.5%	0.1%	0.15%
Total	**100%**	**65.3%**	**25.1%**	**4.3%**	**3.5%**	**0.8%**	**0.88%**

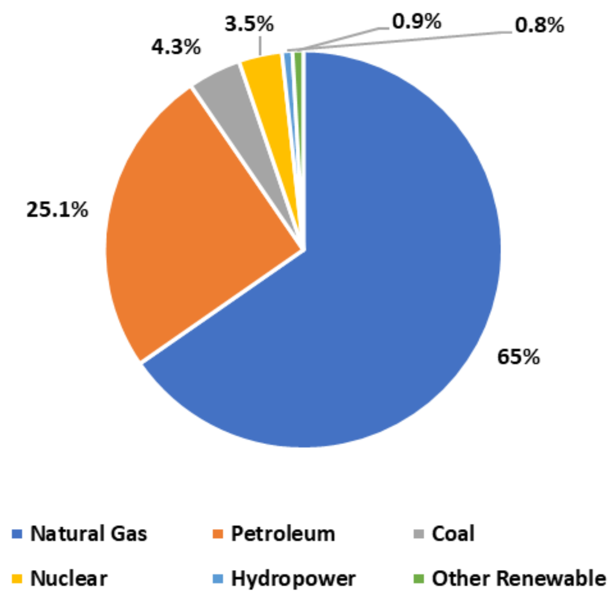

FIGURE 8. PERCENTAGE OF ENERGY SEPARATED BY FUEL TYPE FOR VER SYSTEM

Energy from petroleum comprises approximately 25 percent (23 GJ/91.6 GJ) of the total energy used for the VER production. The largest portion of petroleum is used for the styrene system as a material input. At the VER plant, petroleum is mostly used for transport of the incoming materials. The coal use shown is combusted for electricity use. A discussion of the electricity grid used can be found in Chapter 1. In this grid, approximately 20 percent of this electricity production in the US uses coal as a fuel source, with 34 percent coming from natural gas. A little more than a quarter of the electricity grid used comes from renewable sources. Hydropower as a source makes up over 13 percent of the grid used.

Solid Waste

Solid waste results in this analysis include only process and fuel-related wastes from raw material acquisition through production of the VER. Potential process wastes include sludges and residues from chemical reactions, and potential fuel-related wastes include refinery wastes or coal combustion ash. No postconsumer wastes of the products made from VER are included in this analysis as no product is made from the material in the analysis boundaries.

The process solid waste, those wastes produced directly from the production of materials, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. Some wastes that are recycled/reused or land applied are not included as solid wastes, and no credit is given. The categories of disposal type have been provided separately where possible. Solid wastes from fuel combustion (e.g., ash) are assumed to be landfilled.

Table 7 provides a breakout of the total weight of solid wastes by the disposal fate, as well as hazardous and non-hazardous wastes, for the VER plant average and the incoming materials. Only 2.4 percent of the total solid wastes is considered hazardous waste with 75% of that hazardous waste incinerated in a waste-to-energy facility, and most of the remaining incinerated without energy capture. The remaining 97.6 percent of the solid waste is non-hazardous. Of this, 95 percent of the non-hazardous solid waste is landfilled, while much of the remainder is incinerated without energy capture.

Table 8 and Figure 9 show the percent of total solid wastes separated by the cradle-to-incoming materials and the VER manufacturing plant. Table 8 also provides this breakout for the hazardous and non-hazardous split. The epoxy system input to the manufacture of VER produce the highest amounts of solid waste for the total VER system at 53 percent of the total solid wastes. Within the input material systems, much of the solid wastes are coming from the production and combustion of fuels used to create these materials. Reviewing the process contribution of individual processes, the solid wastes associated with coal extraction and combustion to create electricity make up almost 50 percent of the total solid wastes. The extraction and processing of oil and gas used as a material and as a fuel create 40 percent of the total solid waste. Most of the remaining 10 percent of total solid wastes come from the unit processes of the VER manufacturing plant (6 percent) and the input materials (approximately 4 percent).

TABLE 7. TOTAL SOLID WASTES BY DISPOSAL FATE FOR VER SYSTEM

	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	109	0	0.78	0.0055	0.79	3.5E-04	3.42	104	108
Vinyl Ester Resin Manufacture	17.6	2.25	0.02	0	2.27	0.64	0.16	14.5	15.3
Total	**126**	**2.25**	**0.80**	**0.0055**	**3.06**	**0.64**	**3.58**	**119**	**123**
	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	109	0	0.78	0.0055	0.79	3.5E-04	3.42	104	108
Vinyl Ester Resin Manufacture	17.6	2.25	0.02	0	2.27	0.64	0.16	14.5	15.3
Total	**126**	**2.25**	**0.80**	**0.0055**	**3.06**	**0.64**	**3.58**	**119**	**123**
	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	86%	0%	0.6%	0.00%	0.6%	0.00%	2.7%	82.7%	85.4%
Vinyl Ester Resin Manufacture	14%	1.8%	0.02%	0%	1.8%	0.5%	0.1%	11.5%	12.1%
Total	**100%**	**1.8%**	**0.6%**	**0.00%**	**2.4%**	**0.5%**	**2.8%**	**94%**	**98%**

TABLE 8. PERCENTAGE OF TOTAL SOLID WASTES FOR VER BY PROCESS

	Solid Waste		
	Total	Hazardous	Non-Hazardous
	%	%	%
Incoming Materials Total	**86%**	**26%**	**88%**
Epoxy Resin	*53%*	*10%*	*54%*
Bisphenol A	*7%*	*2%*	*7%*
Styrene	*21%*	*10%*	*21%*
Methylacrylic Acid	*5%*	*4%*	*5%*
Silica sand	*0%*	*0%*	*0%*
Vinyl Ester Resin Manufacture	**14%**	**74%**	**12%**
Process onsite	*6%*	*74%*	*4%*
Fuel use onsite	*1%*	*0%*	*1%*
Electricity	*6%*	*0%*	*6%*
Incoming Material Transport	*1%*	*0%*	*1%*
Total	**100%**	**100%**	**100%**

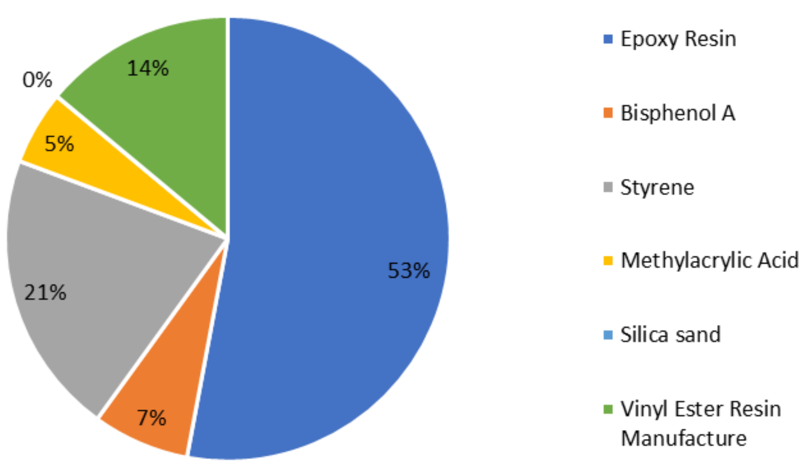

FIGURE 9. PERCENTAGE OF TOTAL SOLID WASTES BY MATERIAL INPUT AND THE VER UNIT PROCESS

Only 14 percent of the total solid waste is created during the VER unit process. A breakout of the processes creating these solid wastes for the VER unit process can be seen in Table 8. Wastes from the process itself make up 6 percent of the total; these include hazardous wastes such as unreacted resin and production wastes which are incinerated. Another 6 percent of the total solid waste representing the VER unit process comes from electricity; the largest portion of which is likely from coal production and combustion.

The non-hazardous waste makes up 98 percent of the total solid waste and so the percentages shown in Table 8 for non-hazardous solid wastes are very close to those of the total solid wastes. The hazardous solid wastes make up only 2 percent of the total and of that, 74 percent is coming from the VER process. These hazardous wastes include filters, sludges and residues from cleaning machinery and drums. Note that hazardous wastes were only shown where known to be hazardous; it is possible that some solid wastes from secondary sources may not have been broken out by hazardous/non-hazardous wastes and so are shown as non-hazardous. Also, 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.

Water Consumption

Consumptive use of water in this study includes freshwater that is withdrawn from a water source or watershed and not returned to that source. Consumptive water use includes water consumed in chemical reactions, water that is incorporated into a product or waste stream, water that becomes evaporative loss, and water that is discharged to a different watershed or water body than the one from which it was withdrawn. Water consumption results shown for each life cycle stage include process water consumption as well as water consumption associated with production of the electricity and fuels used in that stage. Electricity-related water consumption includes evaporative losses associated with thermal generation of electricity from fossil and nuclear fuels, as well as evaporative losses due to establishment of dams for hydropower.

Water consumption results for VER production are shown in Table 9 and Figure 10. The greatest portion of consumption of water within the VER come from the cradle-to-incoming materials (95 percent). When looking at the individual VER input materials, 68 percent of the total is consumed by the cradle-to-gate manufacture of the epoxy resin. Only 5 percent of total water consumption is associated with the VER unit process.

Throughout all the unit processes in the VER system, the largest contributor to water consumption (53 percent) is the total of the production of various chemicals used in the incoming materials. It should be noted that 30 percent of the total water consumption is coming from European datasets where no changes were made during adaptation. One of these European datasets, the cumene input to epoxy, consumes 24 percent of the total water. The water data for these unit processes are specific to Europe, and it is unknown if these would change if they were collected from North American plants. A third of the total water consumption is attributed to hydropower used for electricity generation, a large portion of this is for the epoxy system. Much of the remaining water consumption for the input materials is used during the extraction and processing of oil and gas.

TABLE 9. WATER CONSUMPTION FOR VER SYSTEM

	Total Water Consumption		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	Gallons	*Liters*	*%*
Epoxy Resin	1,533	12,789	68%
Bisphenol A	247	2,062	11%
Styrene	241	2,007	11%
Methylacrylic Acid	113	940	5%
Silica sand	0.1	0.6	0%
Vinyl Ester Resin Manufacture	122	1,017	5%
Total	**2,255**	**18,816**	**100%**

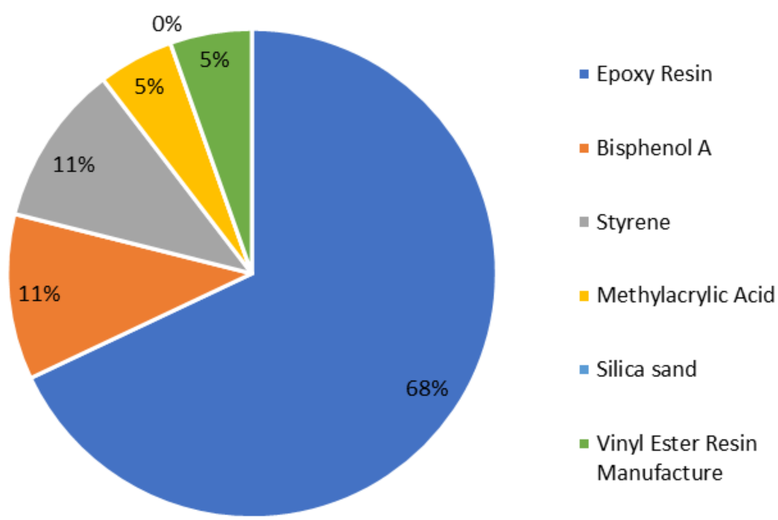

FIGURE 10. WATER CONSUMPTION BY INCOMING MATERIALS AND VER PRODUCTION

At the VER manufacturing unit process, 80 percent of the water consumption is coming from the hydropower used for electricity. The plant itself consumes less than 10 percent of the water consumptions shown in the VER manufacture within Table 9, which equates to less than 1 percent of the total water consumption. The remaining water consumption shown in VER manufacturing comes from the production of oil and gas fuels used at the plant.

Global Warming Potential

The primary atmospheric emissions reported in this analysis that contribute over 99 percent of the total global warming potential (GWP) are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. Other contributors include some HCFCs and other greenhouse gases, but these contribute less than 1 percent of the total shown. Greenhouse gas emissions are mainly from combustion. In the primary data collected for VER and many of its chemical inputs, combustion emissions from flare or another type of emissions control 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 use of the emissions control. Data providers were asked to estimate percentages of greenhouse gases from flare from that of the combustion of fuels. Further discussion of the impact category can be found in Chapter 1.

In Table 10 and Figure 11, the life cycle GWP results for the VER system are provided by input material system and the VER unit process. As shown in Table 3, the greatest input amount is the epoxy, which is a complex chemical requiring a large number of intermediate chemicals as can be seen in Figure 2. It follows that the largest portion of the GWP comes from producing epoxy. The epoxy system also requires the greatest portion of the total energy, which has a correlation to the GWP since carbon dioxide, methane and nitrous oxide are all combustion emissions. The VER manufacturing unit process produces only 10 percent of the GWP total, while the total input materials produce 90 percent.

If the individual unit process contribution is considered, the largest amount (approximately 50 percent) of the GWP emissions is created by combustion of fuels in both industrial and utility boilers throughout the required unit processes to produce the VER. Many of the intermediate chemicals produce greenhouse gas emissions in plant which individually make up between 1 and 5 percent of the GWP and summed equate to about one quarter of the total GWP. These plant GHG emissions are likely due to flares and thermal oxidizers, which have been included as a mix of process and fuel-related emissions.

The GWP specific to the VER plant average are split out in Figure 12. This represents the total percentage by process emissions, electricity production, natural gas combustion onsite, and incoming transport, which make up the 10 percent shown in Table 10. No greenhouse gas process emissions were stated by the VER producers. The other categories make up approximately one-third of the GWP for the VER plant average, which is 10 percent of the total GWP.

TABLE 10. GLOBAL WARMING POTENTIAL FOR VER SYSTEM

	Global Warming Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CO2 eq	*kg CO2 eq*	*%*
Epoxy Resin	1,624	1,624	46%
Bisphenol A	242	242	7%
Styrene	1,003	1,003	28%
Methylacrylic Acid	299	299	9%
Silica sand	0.4	0.4	0%
Vinyl Ester Resin Manufacture	352	352	10%
Total	**3,521**	**3,521**	**100%**

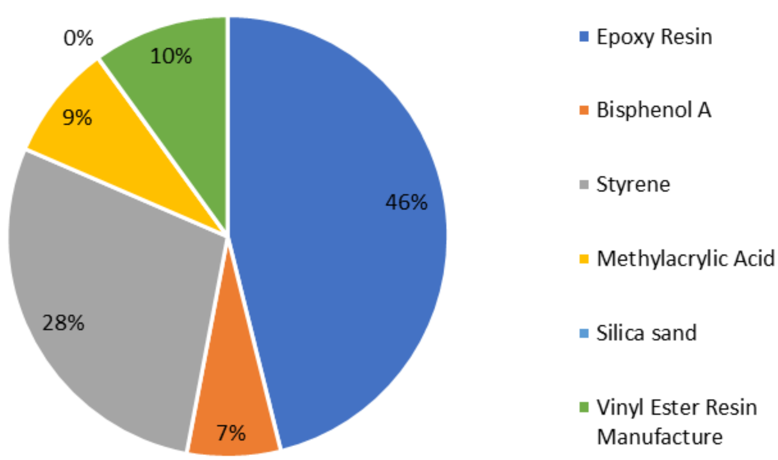

FIGURE 11. PERCENT OF GLOBAL WARMING POTENTIAL BY INCOMING MATERIAL AND VER PRODUCTION

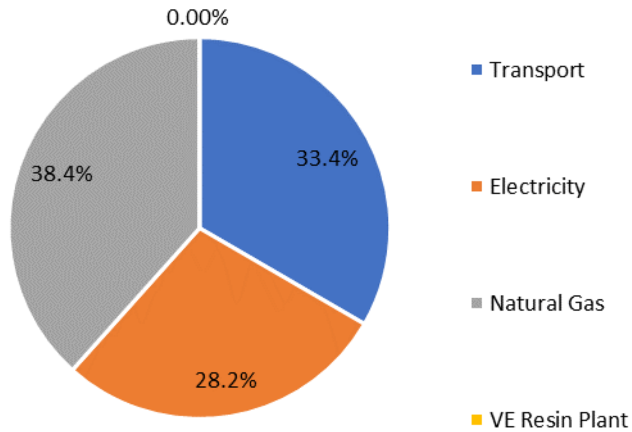

FIGURE 12. GLOBAL WARMING POTENTIAL BY PERCENT FOR THE VER PRODUCTION AVERAGE

Acidification Potential

A description of the Acidification Potential (AP) impact category can be found in Chapter 1. Acidification impacts are typically dominated by fossil fuel combustion emissions, particularly sulfur dioxide (SO2) and nitrogen oxides (NOx). Emissions from combustion of fossil fuels, especially coal, to generate grid electricity is a significant contributor to acidification impacts. The combustion of coal alone for electricity makes up 30 percent of the total AP. Also, emissions from the extraction and processing of natural gas impact the AP category at almost one-quarter of the total AP.

Table 11 shows total acidification potential results for the VER system. Results split by incoming material and VER manufacture are shown graphically in Figure 13. In the AP impact category, 25 percent of the AP is from VER production and 75 percent comes from the incoming materials. Almost three-quarters of the amount of AP coming from the VER manufacture is coming from the transport of incoming materials, while much of the remainder is due to the combustion of coal and natural gas in the electricity grid.

As can be seen in Figure 13, the epoxy system (cradle-to-epoxy) produces approximately 44 percent of the total AP. Much of this amount comes from the extraction and processing of natural gas and the combustion of fuels in the industrial and utility boilers throughout the production. The styrene system makes up 19 percent of the total AP, with the other incoming chemicals each accounting for lesser amounts. As is the case for the other process, most of the AP is coming from the combustion of fuels in boilers or transport or the extraction and processing of natural gas.

TABLE 11. ACIDIFICATION POTENTIAL FOR VER SYSTEM

	Acidification Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb SO2 eq	*kg SO2 eq*	*%*
Cradle-to-Incoming Materials	8.00	8.00	75%
Vinyl Ester Resin Manufacture	2.74	2.74	25%
Total	**10.7**	**10.7**	**100%**

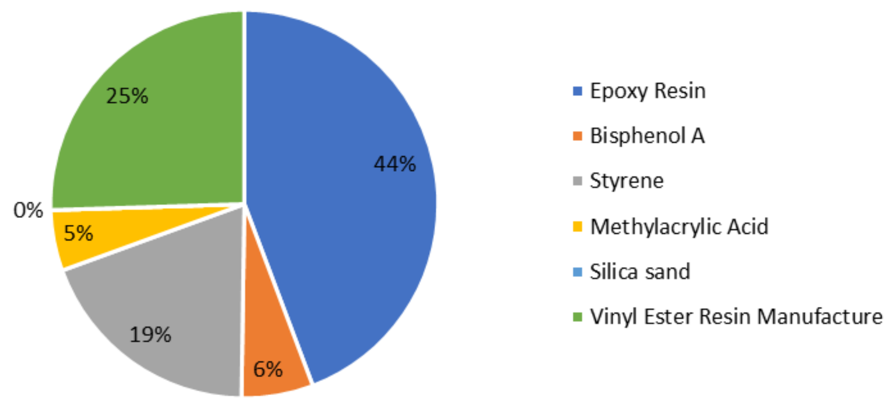

FIGURE 13. PERCENT OF ACIDIFICATION POTENTIAL BY INCOMING MATERIAL AND VER PRODUCTION

Eutrophication Potential

A description of the Eutrophication Potential (EP) impact category can be found in Chapter 1. Atmospheric emissions of nitrogen oxides (NOx) 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.

Table 12 shows total eutrophication potential results for the VER system. EP results split by cradle-to-individual incoming material and the VER manufacture are shown graphically in Figure 14. In the AP impact category, only 4 percent of the AP is from VER production and 96 percent comes from the incoming materials. From this we can see the implication that much of the EP is coming from process emissions and not the combustion of fuels. As no EP-related process emissions were released at the VER plants, the small amount of EP from the

VER manufacturing average is completely from production and combustion of fuels used for transport, boilers and electricity.

TABLE 12. EUTROPHICATION POTENTIAL FOR VER SYSTEM

	Eutrophication Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb N eq	*kg N eq*	*%*
Cradle-to-Incoming Materials	2.46	2.46	96%
Vinyl Ester Resin Manufacture	0.10	0.10	4%
Total	**2.57**	**2.57**	**100%**

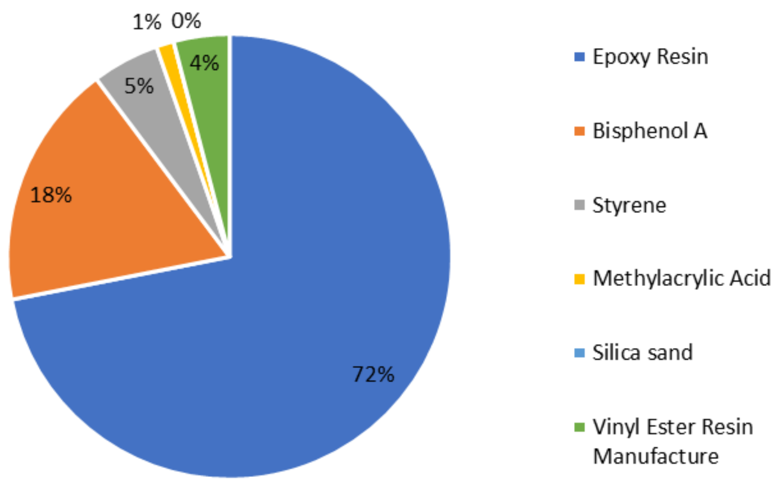

FIGURE 14. PERCENT OF EUTROPHICATION POTENTIAL BY INCOMING MATERIAL AND VER PRODUCTION

The largest portion, 96 percent, of the EP results come from the incoming materials to the VER production. The cradle-to-epoxy resin makes up 72 percent of the total EP amount. This is largely due to emissions released in the manufacture of epoxy resin and from many of the intermediate chemicals used to produce epoxy resin. Most of these intermediate chemical inventory datasets were adapted from the European Ecoinvent database, and no attempt was made to adapt the emission releases in these datasets. As the largest portion of the EP comes from these European unit processes, it is possible that the EP results using North American data for epoxy resin and its incoming materials may differ from this analysis. This is also true for the Bisphenol-A system EP results, which comprise 18 percent of the total EP.

Ozone Depletion Potential

A description of the Ozone Depletion Potential (ODP) impact category can be found in Chapter 1. The main sources of emissions contributing to ODP are minute amounts of tetrachloromethane, HCFCs, and halons are emitted during the extraction of petroleum, which is used as fuel and material in the production of many of the incoming materials, such as benzene and olefins.

Table 13 shows total ozone depletion potential results for the VER system. ODP results split by cradle-to-individual incoming material and the VER manufacture are shown graphically in Figure 15. Ozone depletion results for the VER system are dominated by the crude oil extraction and refining used to create many of the incoming materials, contributing 96 percent of the total ozone depletion impacts, with the remaining 4 percent coming from the manufacturing of VER. Focusing on the average VER manufacturing data, almost all of the 4 percent comes from the production of fuels used in the transport of incoming materials, with a small percentage from the coal combustion to produce electricity.

If the total ODP from incoming materials is focused on, the epoxy and styrene system inputs create approximately 87 percent of the total ODP. Much of this is due to the use of oil for fuels as well as creating the materials. About one-quarter of the ODP associated with epoxy production is coming from the combustion of coal during lime production. The only unit process creating emissions leading to ODP (2 percent of the total) is chlorine production used to create epoxy system.

TABLE 13. OZONE DEPLETION POTENTIAL FOR VER SYSTEM

	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	7.1E-06	7.1E-06	96%
Vinyl Ester Resin Manufacture	3.2E-07	3.2E-07	4%
Total	**7.4E-06**	**7.4E-06**	**100%**

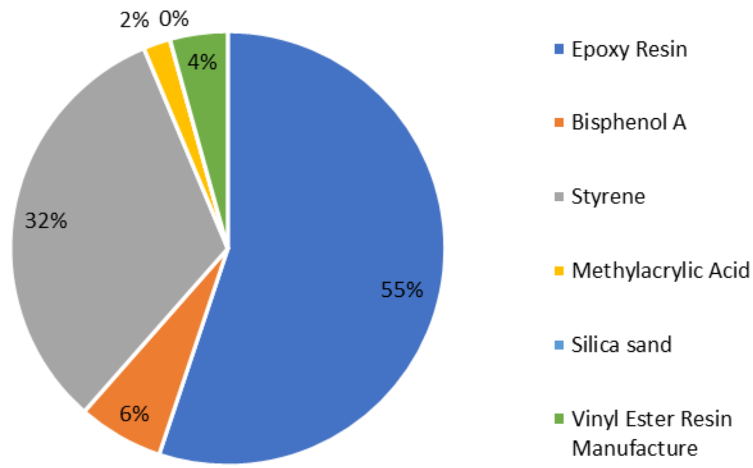

FIGURE 15. PERCENT OF OZONE DEPLETION POTENTIAL BY INCOMING MATERIAL AND VER PRODUCTION

Photochemical Ozone Creation Potential

A description of the Photochemical Ozone Creation Potential (POCP), also known as smog formation, impact category can be found in Chapter 1. Smog formation impacts are generally dominated by emissions associated with fuel combustion, so that impacts are higher for life cycle stages and components that have higher process fuel and transportation fuel requirements. In this case, NOx makes up 93 percent of the smog formation emissions, with VOCs consisting of 4 percent.

Table 14 shows total photochemical ozone creation potential results for the VER system. POCP results split by cradle-to-individual incoming material and the VER manufacture are shown graphically in Figure 16. In the POCP impact category, 25 percent of the POCP is from VER production and 75 percent comes from the incoming materials. More than three-quarters of the amount of POCP coming from the VER manufacture is coming from the transport of incoming materials, while the remainder is split between the combustion of natural gas onsite and emissions from the combustion of coal and natural gas during the creation of electricity off-site.

TABLE 14. PHOTOCHEMICAL OZONE CREATION POTENTIAL FOR VER SYSTEM

	Photochemical Ozone Creation Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb O3 eq	*kg O3 eq*	*%*
Cradle-to-Incoming Materials	174.3	174.3	75%
Vinyl Ester Resin Manufacture	58.4	58.4	25%
Total	**233**	**233**	**100%**

As can be seen in Figure 16, the epoxy system (cradle-to-epoxy) produces approximately 40 percent of the total POCP. Approximately half of this amount comes from the extraction and processing/refining of natural gas and oil. The combustion of fuels in the industrial and utility boilers throughout the epoxy system also makes up over one-third of the 40 percent coming from epoxy. The styrene system makes up 23 percent of the total POCP, and as in the case of the epoxy, most of the associated emissions are coming from the extraction and processing/refining of natural gas and oil. The added BPA and methylacrylic acid each account for 6 percent of the total POCP.

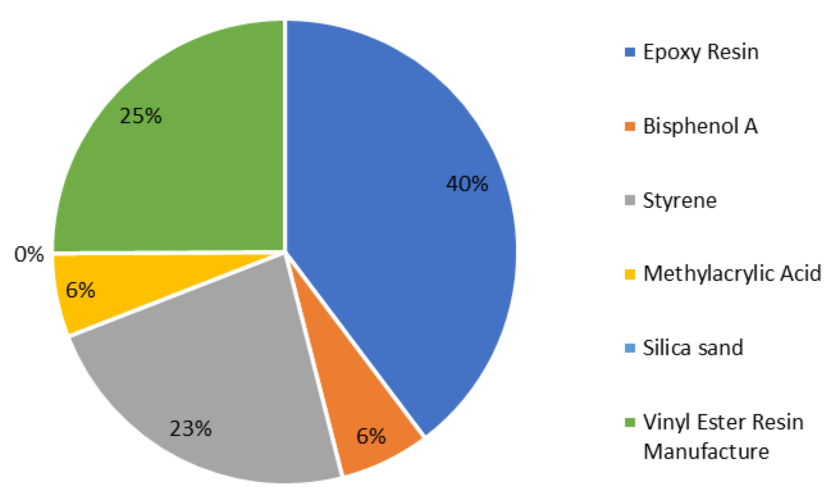

FIGURE 16. PERCENT OF PHOTOCHEMICAL OZONE CREATION POTENTIAL BY INCOMING MATERIAL AND VER PRODUCTION

CHAPTER 3. POLYURETHANE PRECURSOR MATERIALS

This chapter describes the production of two precursors to the manufacture of polyurethane—methylene diphenyl diisocyanate and polyether polyol, as well as presents LCI and LCIA results for cradle-to-gate production of 1,000 pounds and 1,000 kilograms of MDI and polyol for rigid PUR. Average LCI data for the two precursors were not collected for the ACMA study. The average unit process data for MDI and polyether polyol for rigid PUR were collected for the American Chemistry Council and the MDI LCI data can be found in the ACC reports.[25] Due to an insufficient number of companies participating, the average unit process LCI data for polyether polyol is not available publicly. More information on this issue can be found in the ACC report pertaining to polyether polyol for rigid PUR. [26]

GATE-TO-GATE LCI DATA FOR PRODUCTION OF MDI AND POLYETHER POLYOL

Polyurethane resin is a versatile thermosetting resin commonly used in manufacturing composite materials. PUR end markets are primarily construction, automotive, and marine. For reinforced applications, the function of PUR in the composite material is to provide a matrix for structural reinforcements and to distribute and transfer load between reinforced fibers and adjacent structures. PUR is also used in non-reinforced composites applications, such as automotive panels and surface finishes on marine equipment. For non-reinforced applications, PUR is selected for use because it is flexible, moisture resistant, and provides thermal insulation.

Polyurethane resin is produced by the reaction of a polyol, such as polyether polyol, with an isocyanate, such as methylene diphenyl diisocyanate (MDI). MDI is a highly reactive diisocyanate compound, typically produced from the reaction of aniline with formaldehyde and phosgene. Polyether polyol is synthesized from the reaction of an initiator molecule with an alkylene oxide monomer. Common initiator molecules used for polyol production include glycerin or ethylene glycol. The polyether polyol and MDI react to form a polyurethane structure, which undergoes polymerization to form the polyurethane polymer.

Surfactants, blowing agents, or other additives may be incorporated into the mixture, but are not included in this analysis. The properties of PUR depend on the types and proportions of additives included in the mixture during the reaction.

Figure 3 and Figure 4 in Chapter 1 provides a flow diagram of all inputs included in the production of MDI and polyether polyol, respectively. No unit process data tables have been

[25] Cradle-to-Gate Life Cycle Analysis of Methylene Diphenyl Diisocyanate (MDI). Franklin Associates. Submitted to the Plastics Division of the American Chemistry Council. July, 2022

[26] Cradle-to-Gate Life Cycle Analysis of Polyether Polyol for Rigid Foam Polyurethanes. Franklin Associates. Submitted to the Plastics Division of the American Chemistry Council. January, 2023

provided for MDI and polyether polyol in this report. These unit processes can be found in the appendix of the ACC reports specific to those precursors, which is currently available on the ACC website. Further information on the data sources of these materials is shown in Appendix B.

The ACC report on MDI provides an MDI unit process table for two separate allocation methodologies—a mass allocation and an elemental + mass allocation. The results in the ACC report are based on the mass allocation of MDI and its coproduct, hydrochloric acid. However, it is likely that the elemental + mass allocation will be used in subsequent ACC updates for MDI, as it is now being used in Europe. For this reason, the elemental + mass allocation was used to create the results in this ACMA report. If comparisons are made with the results in the sensitivity analysis of the ACC MDI report, the reader will find some differences between the results due to differences in the electricity grid used.

LIFE CYCLE INVENTORY AND IMPACT ASSESSMENT RESULTS FOR MDI AND POLYETHER POLYOL FOR RIGID POLYURETHANE

This section presents baseline results for the following LCI and LCIA results for both 1,000 pounds and 1,000 kilograms of MDI and polyether polyol for rigid polyurethane (hereafter referenced as polyether polyol).

Life cycle inventory results:

- Energy demand
    - Cumulative 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

A description of each of the LCI and LCIA categories can be found in Chapter 1.

Throughout the results sections, the tables break out system results into the following unit processes, for MDI and polyether polyol:

- Cradle-to-incoming materials – includes the raw materials through the production of the incoming materials.

- MDI production – is the gate-to-gate unit process and includes the production of fuels used in the process and transportation of the incoming materials to create phosgene/MDA/MDI.

or

- Polyether polyol production – is the gate-to-gate unit process and includes the production of fuels used in the process and transportation of the incoming materials to the production facility.

Some of the figures include result details for each of the individual input material systems. This split was provided for the main inventory categories, as well as the global warming potential. Each impact category section has been divided into subsections for the MDI and polyether polyol results for that impact category.

Tables and figures are provided for both MDI and rigid polyol 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 material stated in the term (e.g., cradle-to-MDI and MDI system are interchangeable). The phrase "gate-to-gate" is defined as including only the onsite process/fuels.

Energy Demand

Energy Demand has been detailed by renewable and non-renewable energy, as well as by fuel type. A short discussion is provided about the energy of material resource results, which is explained in Chapter 1, as compared to the fuel and process energy results.

Cumulative Energy Demand

Cumulative energy demand results include all renewable and non-renewable energy sources used for process and fuel energy, as well as energy of material resource (also called 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 most of the incoming chemicals (e.g., the energy content of oil and gas used as material feedstocks) to the MDI or rigid polyol, which is discussed in Chapter 1.

MDI

The total energy required to produce MDI is 32.1 million Btu per 1,000 pounds of MDI or 74.8 GJ per 1,000 kilograms of MDI. Table 15 shows the total energy demand for the MDI system. The MDI production energy has been split out from the energy required for incoming materials. Approximately 6 percent of the total energy is required to produce MDI at the plant. The remaining 94 percent is associated with the manufacture of MDI input materials.

Table 15 also provides details about the non-renewable and renewable energy use within the total energy. 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), as well as use of uranium to generate the share of nuclear energy in the average U.S. kWh. For the MDI system, 99 percent of the total energy comes from non-renewable sources. The renewable energy (0.74 GJ/1000 kg) used in the MDI system comes from a mix of hydropower, wind, and other renewable sources (geothermal, solar, etc.) from electricity production.

TABLE 15. TOTAL ENERGY DEMAND FOR MDI

	Basis: 1,000 pounds		
	Total Energy	Non-Renewable Energy	Renewable Energy
	MM Btu	*MM Btu*	*MM Btu*
Cradle-to-Incoming Materials	30.3	30.0	0.24
Phosgene/MDA/MDI Production	1.89	1.81	0.083
Total	**32.1**	**31.8**	**0.32**
	Basis: 1,000 kilograms		
	Total Energy	Non-Renewable Energy	Renewable Energy
	GJ	*GJ*	*GJ*
Cradle-to-Incoming Materials	70.4	69.8	0.55
Phosgene/MDA/MDI Production	4.39	4.20	0.19
Total	**74.8**	**74.0**	**0.74**
	Percentage		
	Total Energy	Non-Renewable Energy	Renewable Energy
	%	*%*	*%*
Cradle-to-Incoming Materials	94.1%	93.4%	0.7%
Phosgene/MDA/MDI Production	5.9%	5.6%	0.3%
Total	**100%**	**99.0%**	**1.0%**

In Figure 17 a breakout of the percentage of total energy is provided by individual input materials as well as the phosgene/MDA/MDI production. When considering the individual MDI input materials, the largest amount of incoming material is aniline in the MDI production (over 0.8 kg aniline per 1 kg MDI using the elemental + mass allocation). This coincides with the aniline system having the highest energy demand, making up 71 percent of the total energy demand. It should be noted that the energy shown for each of the incoming materials is a cradle-to-material percentage; and, therefore, includes the feedstock energy inherent in the material, as well as the process and fuel-related energy. The carbon monoxide and formaldehyde make up 12 and 8 percent of the total energy respectively. These incoming materials are also input at larger amounts than the remaining incoming materials. Small amounts of sodium hydroxide, hydrochloric acid and nitrogen produce 1 percent of less of the total energy. The phosgene/MDA/MDI process which makes up 6 percent of the energy is from a combination of half from electricity use and half from onsite boilers using natural gas or a similar fuel.

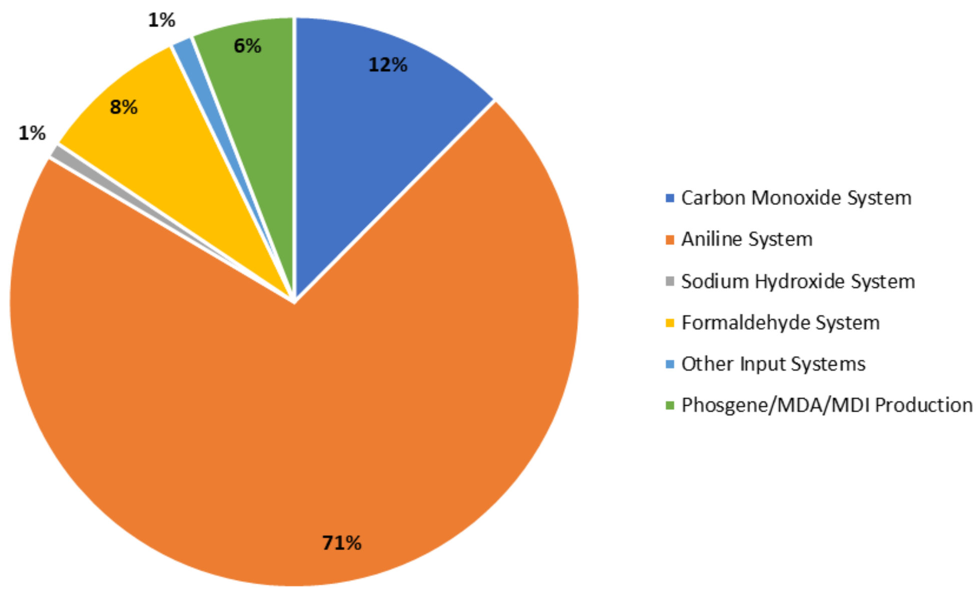

FIGURE 17. TOTAL ENERGY DEMAND BY PERCENT OF INCOMING MATERIAL SYSTEM AND PHOSGENE/MDA/MDI MANUFACTURE

The energy representing natural gas and petroleum used as raw material inputs for the production of incoming chemicals used to produce MDI are included in the cradle-to-incoming material amounts in Table 15. The energy inherent in these raw materials are called material feedstock energy or energy of material resource. Of the total energy (74.8 GJ) for 1,000 kg of MDI, 57 GJ is material feedstock energy. Figure 18 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 MDI. Approximately 76 percent of the total energy is inherent energy in the natural gas and petroleum used as a feedstock to create chemicals such as pyrolysis gasoline, ammonia, and benzene, which in turn are used to create MDI. Of the feedstock sources for MDI, 61 percent come from natural gas, while 39 percent of the feedstock sources come from oil.

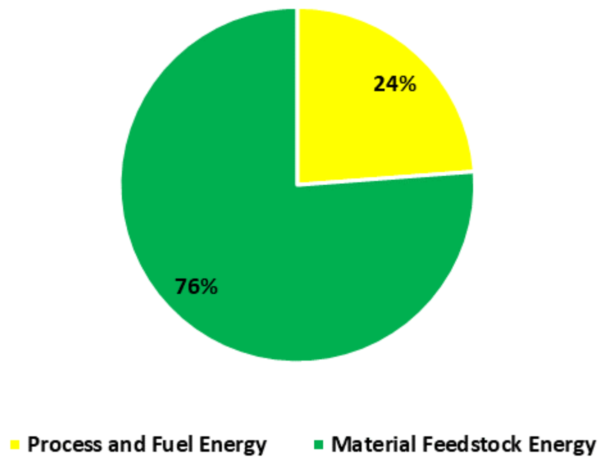

FIGURE 18. PROCESS/FUEL AND MATERIAL FEEDSTOCK PERCENTAGES FOR MDI

POLYETHER POLYOL

The total energy required to produce polyether polyol is 31.9 million Btu per 1,000 pounds or 74.3 GJ per 1,000 kilograms of polyether polyol. Table 16 shows the total energy demand for the polyether polyol system. The polyether polyol production energy has been split out from the energy required for incoming materials. A little less than 5 percent of the total energy is required to produce the polyol at the plant. The remaining 96 percent is associated with the manufacture of input materials to polyether polyol.

Table 16 also provides details about the non-renewable and renewable energy use within the total energy. For the polyether polyol system, 98 percent of the total energy comes from non-renewable sources. The renewable energy (1.33 GJ/1000 kg) used in the polyether polyol system comes from a mix of hydropower, wind, and other renewable sources (geothermal, solar, etc.) from electricity production.

In Figure 19, a breakout of the percentage of total energy is provided by individual input materials as well as the polyether polyol production. When considering the individual polyol input materials, the largest amount of incoming material is propylene oxide in the polyol production; the cradle-to-manufacture of propylene oxide makes up 93 percent of the total energy required to produce polyether polyol. Sucrose and glycerine make up 2 and less than 1 percent of the total energy respectively.

TABLE 16. TOTAL ENERGY DEMAND FOR POLYETHER POLYOL

	Basis: 1,000 pounds		
	Total Energy	Non-Renewable Energy	Renewable Energy
	MM Btu	*MM Btu*	*MM Btu*
Cradle-to-Incoming Materials	30.5	30.0	0.51
Polyether Polyol Production	1.47	1.41	0.067
Total	**31.9**	**31.4**	**0.57**
	Basis: 1,000 kilograms		
	Total Energy	Non-Renewable Energy	Renewable Energy
	GJ	*GJ*	*GJ*
Cradle-to-Incoming Materials	70.9	69.7	1.18
Polyether Polyol Production	3.43	3.27	0.16
Total	**74.3**	**73.0**	**1.33**
	Percentage		
	Total Energy	Non-Renewable Energy	Renewable Energy
	%	*%*	*%*
Cradle-to-Incoming Materials	95.4%	93.8%	1.6%
Polyether Polyol Production	4.6%	4.4%	0.2%
Total	**100%**	**98.2%**	**1.8%**

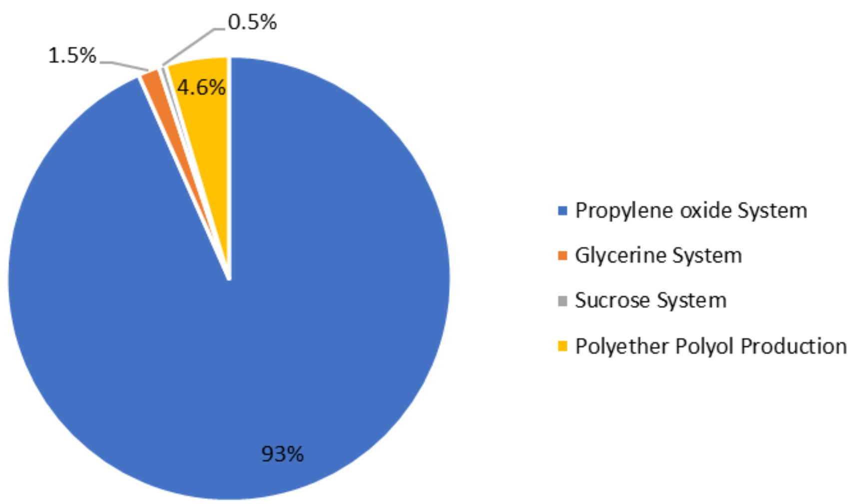

FIGURE 19. TOTAL ENERGY DEMAND BY PERCENT OF INCOMING MATERIAL SYSTEM AND POLYETHER POLYOL MANUFACTURE

The energy content of natural gas and petroleum used as raw material inputs for the production of propylene used to produce the incoming material propylene oxide for the polyether polyol is included in the cradle-to-incoming material amounts in Figure 20. The energy inherent in these raw materials is called material feedstock energy or energy of material resource. Of the total energy (74.3 GJ) for 1,000 kg of polyether polyol, 30.5 GJ is material feedstock energy. Approximately 41 percent of the total energy is inherent energy in the natural gas and petroleum used as a feedstock to create propylene, which in turn are used to create propylene oxide making polyether polyol. Of the feedstock sources for propylene, 87 percent comes from natural gas, while 13 percent of the feedstock sources come from oil.

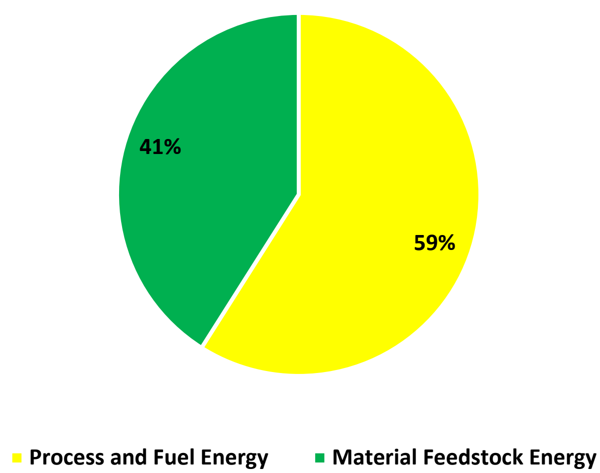

FIGURE 20. PROCESS/FUEL AND MATERIAL FEEDSTOCK PERCENTAGES FOR POLYETHER POLYOL

Energy Demand by Fuel Type

Natural gas and petroleum together make up the largest portion of the total energy used for both MDI and polyether polyol. As shown in Figures 18 and 20, this is partially due to the material feedstock energy used to create the olefins and other intermediate chemical inputs to MDI and polyether polyol. These material feedstock fuels are part of the energy shown in the natural gas and petroleum split out in the following tables.

A discussion of the electricity grid used for this study can be found in Chapter 1. In this grid, approximately 20 percent of the electricity production in the US uses coal as a fuel source, while over a third of the grid comes from natural gas and 18 percent from uranium. The hydropower, nuclear, and other energy are all used to create electricity, with the exception of a small amount of landfill gas used in the olefins production shown within other renewables.

MDI

The total energy demand by fuel type for MDI is shown in Table 17. Natural gas and petroleum together make up 95 percent of the total energy used. The gate-to-gate production energy for phosgene/MDA/MDI in the following table represents the energy required for transportation of raw materials to the plant, the energy required to produce the output, and the production of the fuels needed to manufacture the phosgene/MDA/MDI. 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. At the MDI plant, 75 percent of the energy used (3.31 GJ/4.39 GJ) comes from natural gas. Of that natural gas used at the MDI plant, 63 percent is combusted on-site, while 35 percent is required to create electricity either through the grid or through a nearby cogeneration plant. The largest portion of petroleum is used for the production of benzene as a material input.

TABLE 17. ENERGY DEMAND BY FUEL TYPE FOR MDI

	Basis: 1,000 pounds						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	MM Btu	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*
Cradle-to-Incoming Materials	30.3	18.5	10.46	0.53	0.49	0.12	0.12
Phosgene/MDA/MDI Production	1.89	1.42	0.022	0.19	0.17	0.042	0.042
Total	**32.1**	**20.0**	**10.49**	**0.72**	**0.66**	**0.16**	**0.16**
	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	70.4	43.1	24.3	1.24	1.14	0.27	0.28
Phosgene/MDA/MDI Production	4.39	3.31	0.051	0.43	0.40	0.10	0.10
Total	**74.8**	**46.4**	**24.4**	**1.67**	**1.55**	**0.37**	**0.38**
	Percentage of Total						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	%	*%*	*%*	*%*	*%*	*%*	*%*
Cradle-to-Incoming Materials	94%	58%	32.5%	1.7%	1.5%	0.4%	0.4%
Phosgene/MDA/MDI Production	6%	4.4%	0.1%	0.6%	0.5%	0.1%	0.1%
Total	**100%**	**62%**	**32.6%**	**2.2%**	**2.1%**	**0.5%**	**0.5%**

POLYETHER POLYOL

The total energy demand by fuel type for polyether polyol is shown in Table 18. Almost 83 percent of the total energy used comes from natural gas. The gate-to-gate production energy for polyether polyol in the following table and figure represents the energy required for transportation of raw materials to polyether polyol manufacturers, the energy required to produce the polyether polyol, and the production of the fuels combusted during the polyether polyol manufacture. At the polyether polyol plant, 70 percent of the energy used

(2.4 GJ/3.43 GJ) comes from natural gas. Of that natural gas used at the polyether polyol plant, 46 percent is combusted on-site, while 53 percent is required to create electricity through the grid and cogeneration. A large amount of electricity is used in the chlor-alkali process, the products of which are major inputs to some of the technologies producing propylene oxide used to create polyether polyol.

TABLE 18. ENERGY DEMAND BY FUEL TYPE FOR RIGID POLYOL

	Basis: 1,000 pounds						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	MM Btu	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*
Cradle-to-Incoming Materials	30.5	25.4	2.33	1.21	1.08	0.26	0.23
Rigid Polyol Production	1.47	1.03	0.083	0.15	0.14	0.034	0.034
Total	**31.9**	**26.4**	**2.41**	**1.36**	**1.22**	**0.29**	**0.27**
	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	70.9	59.0	5.42	2.82	2.51	0.61	0.54
Rigid Polyol Production	3.43	2.40	0.19	0.35	0.33	0.078	0.080
Total	**74.3**	**61.4**	**5.61**	**3.17**	**2.83**	**0.69**	**0.62**
	Percentage of Total						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	%	*%*	*%*	*%*	*%*	*%*	*%*
Cradle-to-Incoming Materials	95.4%	79.4%	7.3%	3.8%	3.4%	0.8%	0.7%
Rigid Polyol Production	4.6%	3.2%	0.3%	0.5%	0.4%	0.1%	0.1%
Total	**100%**	**82.6%**	**7.6%**	**4.3%**	**3.8%**	**0.9%**	**0.8%**

Solid Waste

Solid waste results in this analysis include only process and fuel-related wastes from raw material acquisition through production of the MDI and polyether polyol. Potential process wastes include sludges and residues from chemical reactions, and potential fuel-related wastes include refinery wastes or coal combustion ash. No postconsumer wastes of the products made from MDI and polyether polyol are included in this analysis as no product is made from the material in the analysis boundaries.

The process solid waste, those wastes produced directly from the production of materials, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. Some wastes that are recycled/reused or land applied are not included as solid wastes, and no credit is given. The categories of disposal type have been provided separately where possible. Solid wastes from fuel combustion (e.g., ash) are assumed to be landfilled. The solid wastes have also been separated into hazardous and non-hazardous waste categories, as well as by the cradle-to-incoming materials and the MDI or polyether polyol plant. This separation of hazardous and non-hazardous was done only where primary data were collected, or if a secondary data source was clear that the solid waste was of a hazardous nature. The process solid wastes from oil and natural gas were classified as non-hazardous due to exclusions found in resource conservation and recovery act (RCRA) hazardous wastes regulations or other EPA hazardous wastes regulations. No solid wastes were stated as hazardous in the data sources for oil and gas.

MDI

Solid waste generation for cradle-to-gate production of MDI is shown by process stage in Table 19. The majority of solid waste, 88 percent, comes from the production of incoming materials used to produce phosgene/MDA/MDI. The remaining 12 percent of the total solid waste is created during the phosgene/MDA/MDI unit process. Of that amount associated only with the plant, less than 4 percent is process solid waste, while 85 percent of this amount comes from fuels combusted for the electricity used in the plant, with the remaining mostly from natural gas combustion onsite.

Table 19 also provides a breakout of the total solid wastes by hazardous and non-hazardous solid wastes. Only 1.9 percent of the total solid wastes were considered hazardous waste. Of the total hazardous solid waste, more than half comes from the aniline plant, while a quarter comes from the olefins plant and 19 percent from the MDI plant.

The total solid wastes by the disposal fate for MDI system is also provided in Table 19. Of the total hazardous waste, 88 percent is incinerated without energy capture, while the remainder is sent to a hazardous landfill. Focusing specifically on the non-hazardous solid waste produced, 98 percent of the total non-hazardous solid waste is landfilled, while much of the remainder is incinerated without energy capture.

Figure 21 provides a visual of the total solid waste split by the main incoming material systems and the phosgene/MDA/MDI manufacture. Focusing on direct input systems, which make up 88 percent of the solid waste, the aniline system (cradle-to-aniline) produces 66 percent of the total solid wastes, while the carbon monoxide and formaldehyde systems contribute 8 and 9 percent of the total solid waste. Although it cannot be seen directly in the figure, we can consider the process contribution of the individual unit processes. When looking at the process contributions, the extraction and processing of the natural gas and crude oil raw materials create 60 percent of the solid wastes from the cradle-to-incoming materials. The coal production and combustion, which come from electricity use, account for almost 35 percent of the total solid waste. Interestingly, the aniline process itself only creates 1 percent of the total solid waste, while the pyrolysis gas unit process used to create the aniline makes up another 3 percent.

TABLE 19. TOTAL SOLID WASTES BY DISPOSAL FATE FOR MDI

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	66.2	0	1.17	6.3E-03	1.17	1.5E-04	1.54	63.5	65.1
Phosgene/MDA/MDI Production	8.75	0	0.11	0.16	0.27	0	0	8.48	8.48
Total	**75.0**	**0**	**1.28**	**0.17**	**1.45**	**1.5E-04**	**1.54**	**72.0**	**73.5**

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	66.2	0	1.17	6.3E-03	1.17	1.5E-04	1.54	63.5	65.1
Phosgene/MDA/MDI Production	8.75	0	0.11	0.16	0.27	0	0	8.48	8.48
Total	**75.0**	**0**	**1.28**	**0.17**	**1.45**	**1.5E-04**	**1.54**	**72.0**	**73.5**

Percentage of Total

		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	%	*%*	*%*	*%*	*%*	*%*	*%*	*%*	*%*
Cradle-to-Incoming Materials	88%	0%	1.56%	0.0%	1.6%	0.0%	2.1%	85%	87%
Phosgene/MDA/MDI Production	12%	0%	0.15%	0.2%	0.4%	0%	0%	11%	11%
Total	**100%**	**0%**	**1.7%**	**0.2%**	**1.9%**	**0.0%**	**2.1%**	**96%**	**98%**

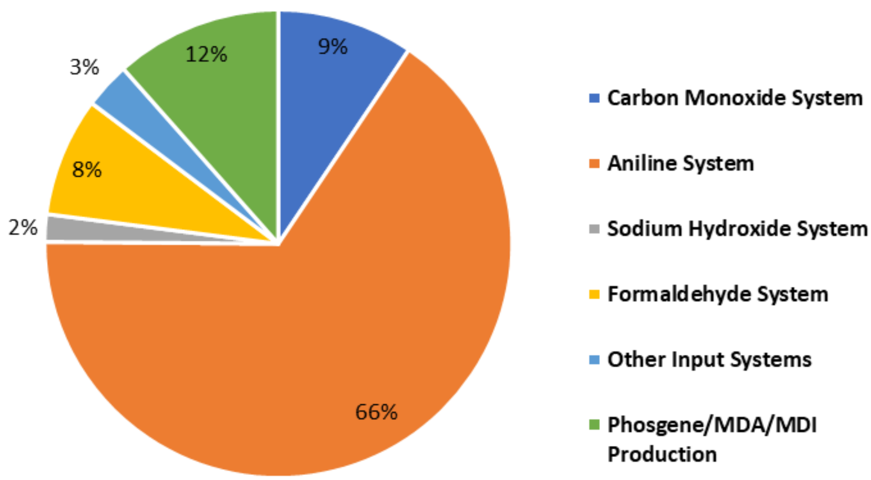

FIGURE 21. PERCENTAGE OF TOTAL SOLID WASTES BY INCOMING MATERIAL SYSTEM AND AVERAGE MDI PRODUCTION

POLYETHER POLYOL

The total solid waste and breakout of solid waste by fate, waste type, and phase are shown in Table 20. The majority of solid waste, 91 percent, comes from the production of incoming materials used to produce polyether polyol. Only 9 percent of the total solid waste is associated with the polyether polyol unit process. Of that amount associated with the plant, only 13 percent is process solid waste, while 80 percent of this amount comes from fuels combusted for the electricity used in the plant, with the remaining from natural gas combustion or production of transport fuels.

Table 20 also provides a breakout of the total solid wastes by hazardous and non-hazardous solid wastes. Only 2.4 percent of the total solid wastes were considered hazardous wastes. Of that percentage, a little more than a third comes from the propylene plant and most of the remaining amount coming from the polyether polyol plant.

The total solid wastes by the disposal fate for the polyether polyol system is also provided in Table 20. Of the hazardous waste, 64 percent is incinerated with energy capture. Most of the remainder of the hazardous waste is incinerated without energy capture, while a small amount is landfilled. Focusing specifically on the non-hazardous solid waste produced, 96 percent of the non-hazardous solid waste is landfilled, while most of the remaining 4 percent is incinerated without energy capture.

TABLE 20. TOTAL SOLID WASTES BY DISPOSAL FATE FOR RIGID POLYOL

	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	82.5	0	0.79	0.0021	0.79	3.5E-04	3.39	78.3	81.7
Polyether Polyol Production	8.54	1.40	0	0.0036	1.40	0	0	7.14	7.14
Total	**91.0**	**1.40**	**0.79**	**0.0057**	**2.20**	**3.5E-04**	**3.39**	**85.4**	**88.8**
	Basis: 1,000 kilograms								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	kg	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*	*kg*
Cradle-to-Incoming Materials	82.5	0	0.79	0.0021	0.79	3.5E-04	3.39	78.3	81.7
Polyether Polyol Production	8.54	1.40	0	0.0036	1.40	0	0	7.14	7.14
Total	**91.0**	**1.40**	**0.79**	**0.0057**	**2.20**	**3.5E-04**	**3.39**	**85.4**	**88.8**
	Percentage of Total								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	%	*%*	*%*	*%*	*%*	*%*	*%*	*%*	*%*
Cradle-to-Incoming Materials	90.6%	0%	0.9%	0.0%	0.9%	0.0%	3.7%	86%	90%
Polyether Polyol Production	9.4%	1.5%	0%	0.0%	1.5%	0%	0%	7.8%	7.8%
Total	**100%**	**1.5%**	**0.9%**	**0.0%**	**2.4%**	**0.0%**	**3.7%**	**94%**	**98%**

Figure 22 provides a visual of the total solid waste split by the main incoming material systems and the polyether polyol manufacture. Focusing on direct input systems, which make up 91 percent of the solid waste, the propylene oxide system (cradle-to-propylene oxide) produces 87 percent of the total solid wastes, while the sucrose and glycerine systems contribute less than 5 percent of the total solid waste. Although it cannot be seen directly in the figure, we can consider the process contribution of the individual unit processes. When looking at the process contributions, the coal production and combustion, which come from electricity use, account for more than 50 percent of the total solid waste. The solid wastes created from the extraction and processing of the natural gas and crude oil raw materials create 37 percent of the solid wastes from the cradle-to-incoming materials. The propylene plant process wastes make up 5 percent of the total solid wastes, while the process wastes for the polyether polyol products less than 2 percent of the total solid wastes.

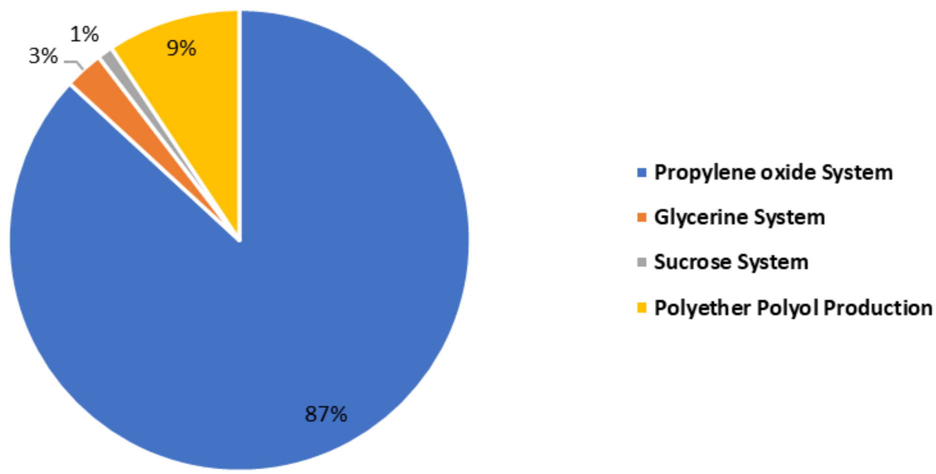

FIGURE 22. PERCENTAGE OF TOTAL SOLID WASTES BY INCOMING MATERIAL SYSTEM AND AVERAGE POLYETHER POLYOL PRODUCTION

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.

MDI

Water consumption results for MDI and Rigid Polyol production are shown in Table 21. The greatest portion of consumption of water within the MDI come from the cradle-to-incoming materials (71 percent), while the remaining 29 percent comes from the phosgene/MDA/MDI production. Throughout all the unit processes, the largest contributor to water consumption is the electricity used, which makes up over a quarter of the total water consumption. This is due to evaporative losses in the use of hydropower.

In Figure 23, the individual input material systems are broken out by percentage. When focusing on this type of breakout, about 50 percent of the total water is consumed by the cradle-to-gate manufacture of the aniline. Aniline manufacture includes the production of pygas from the olefin cracker, which does include some plants that release water to a different watershed than the initial water source, which is considered consumption in the methodology used. The remaining main incoming materials make up between 5 and 7 percent of the total water consumption.

The MDI average data also includes some plants that release water to a different watershed. The MDI plant water consumption makes up 21 percent of the total water consumed with a 7 percent coming from electricity production off-site and the remaining percentage from the production of fuels for the production of the natural gas combusted and the fuels for transport.

TABLE 21. WATER CONSUMPTION FOR MDI SYSTEM

	Total Water Consumption		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	Gallons	*Liters*	*%*
Cradle-to-Incoming Materials	937	7,815	71%
Phosgene/MDA/MDI Production	378	3,150	29%
Total	**1,314**	**10,966**	**100%**

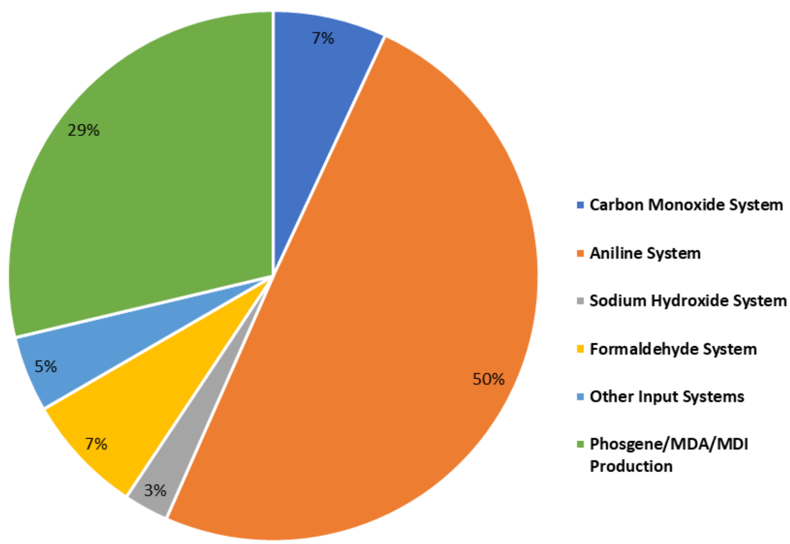

FIGURE 23. WATER CONSUMPTION BY INPUT MATERIAL SYSTEM FOR MDI PRODUCTION

POLYETHER POLYOL

Water consumption results for polyether polyol production are shown in Table 22. The greatest portion of consumption of water within the polyether polyol comes from the cradle-to-incoming materials (98 percent). In Figure 24 the individual input material systems are broken out by percentage. More than 60 percent of the total water consumption is required for the sugar cane cultivation used to make sucrose. Within the propylene oxide system, the brine required for chlor-alkali requires 16 percent of the total water, while other unit processes require another 7 percent. Another large contributor for water consumption is the electricity used during all processes mostly due to evaporative losses in the use of hydropower, which makes up more than 12 percent of the total water consumption, which is split amount all processes that use electricity. Some of the primary water consumption data for specific unit processes within the incoming materials include some plants that release water to a different watershed than the initial water source, which is considered consumption in the methodology used. The polyether polyol average data also includes some plants that release water to a different watershed. The polyether polyol water consumption at the plant makes up less than one tenth of a percent of the total. Much of the water consumption for the polyether polyol average manufacture (2% of the total) comes from the electricity use or production of other fuels used at the plant.

TABLE 22. WATER CONSUMPTION FOR POLYETHER POLYOL SYSTEM

	Total Water Consumption		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	Gallons	***Liters***	***%***
Cradle-to-Incoming Materials	5,021	41,900	98%
Polyether Polyol Production	79.6	664	2%
Total	**5,101**	**42,564**	**100%**

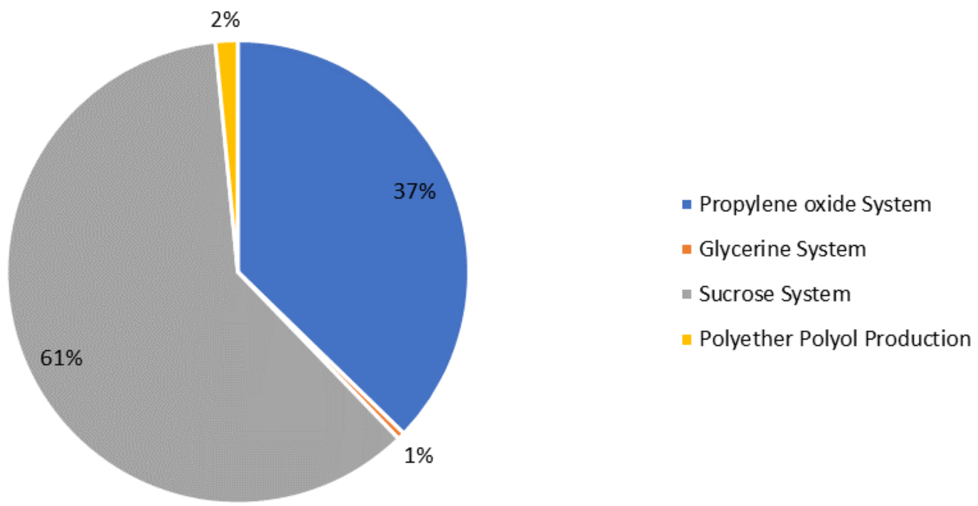

FIGURE 24. WATER CONSUMPTION BY INCOMING MATERIAL SYSTEM AND AVERAGE POLYETHER POLYOL PRODUCTION

Global Warming Potential

The primary atmospheric emissions reported in this analysis that contribute over 99 percent of the total global warming potential (GWP) for each system are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. Other contributors include some HCFCs and other greenhouse gases, but these contribute less than 1 percent of the total shown. Greenhouse gas emissions are mainly from combustion. In the primary data collected for MDI and polyether polyol and many of the chemical inputs to the polyurethane precursors, combustion emissions from flare or another type of emissions control 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 use of the emissions control. Data providers were asked to estimate percentages of greenhouse gases from flare from that of the combustion of fuels. Further discussion of the impact category can be found in Chapter 1.

MDI

In Table 23, the life cycle GWP results for the MDI system are displayed. Of the total, 87 percent of the GWP is attributed to emissions from the incoming materials to the phosgene/MDA/MDI unit process, with the remaining associated with said unit process. Approximately a quarter of the GWP is created by both industrial and utility boiler emissions released throughout the life cycle of MDI. The extraction and processing/refining of natural gas and oil used as a material and to create fuels make up a little less than 20 percent of the total . These fuel combustion and natural gas/oil processes are part of each of the individual incoming material system. Figure 25 provides details of the percentage of GWP associated with each incoming material system and the production of phosgene/MDA/MDI. Considering the GWP from incoming materials to MDI, the production of aniline (cradle-to-aniline) accounts for 57 percent of the total GWP. The carbon monoxide system produces 21 percent of the total GWP, while 7 percent associated with the production of formaldehyde.

TABLE 23. GLOBAL WARMING POTENTIAL FOR MDI SYSTEM

	Global Warming Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CO2 eq	*kg CO2 eq*	*%*
MDI Cradle-to-Incoming Materials	2,180	2,180	87%
Phosgene/MDA/MDI Production	332	332	13%
Total	**2,512**	**2,512**	**100%**

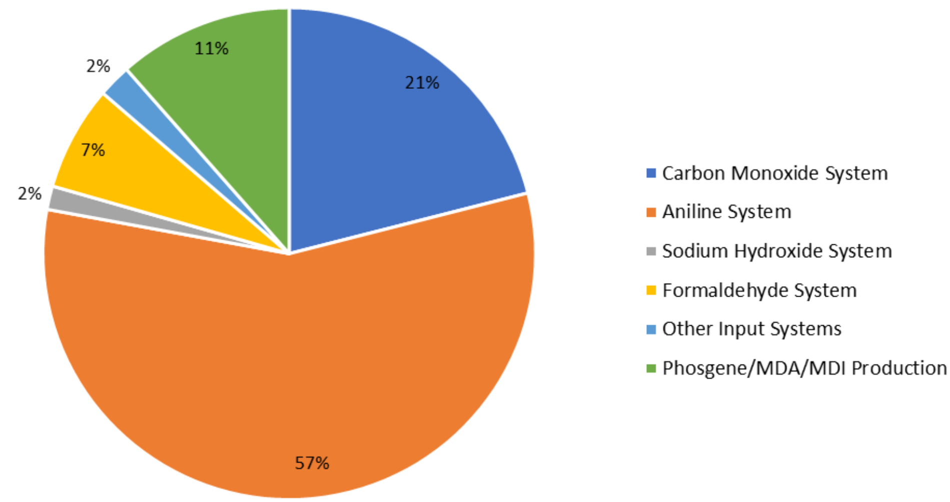

FIGURE 25. GLOBAL WARMING POTENTIAL BY INCOMING MATERIAL SYSTEM AND AVERAGE MDI PRODUCTION

Of the total GWP, 13 percent is associated with the phosgene/MDA/MDI unit process. Of the greenhouse gases for this unit process specifically, 57 percent are released at the MDI plants. About 10 percent GWP at the plant are due to the use of a thermal oxidizer and/or flare, which are considered a mix of process and fuel-based emissions. The largest portion (46 percent of the MDI unit process GWP) of GWP at the plant are from natural gas boilers onsite. Most of the remaining GWP for this unit process come from the production of electricity used at the plants.

POLYETHER POLYOL

In Table 24, the life cycle GWP results for the polyether polyol system are displayed. Of the total, 94 percent of the GWP are attributed to emissions associated with production of the incoming materials, including the system processes for each incoming material (propylene oxide, sucrose, and glycerine) with the remaining associated with the production of the polyether polyol. Figure 26, which shows the GWP percent by incoming material system and the polyol production, details that 84 percent of this total GWP is associated with the cradle-to-propylene oxide material, which accounts for 76 percent of the inputs by weight. Almost 50 percent of the GWP amount comes from the combustion of natural gas within both industrial and utility boilers in the individual unit processes.

For the polyether polyol unit process, only 6 percent of the total GWP from greenhouse gases are released from the polyol unit process average. The process greenhouse gases released on-site at the polyether polyol plants comprise less than 10 percent of the polyol unit process GWP; this is due to the thermal oxidizer, which is considered a mix of process and fuel-based emissions. The larger amounts of GWP from the polyether polyol plants are from either natural gas combustion (16 percent of the polyether polyol amount) or electricity (67 percent of the polyether polyol amount). While the remaining 7 percent of the polyether polyol GWP comes from fuel combustion for incoming transport of materials.

TABLE 24. GLOBAL WARMING POTENTIAL FOR POLYETHER POLYOL SYSTEM

	Global Warming Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CO2 eq	*kg CO2 eq*	*%*
Cradle-to-Incoming Materials	2,653	2,653	94%
Polyether Polyol Production	183	183	6%
Total	**2,836**	**2,836**	**100%**

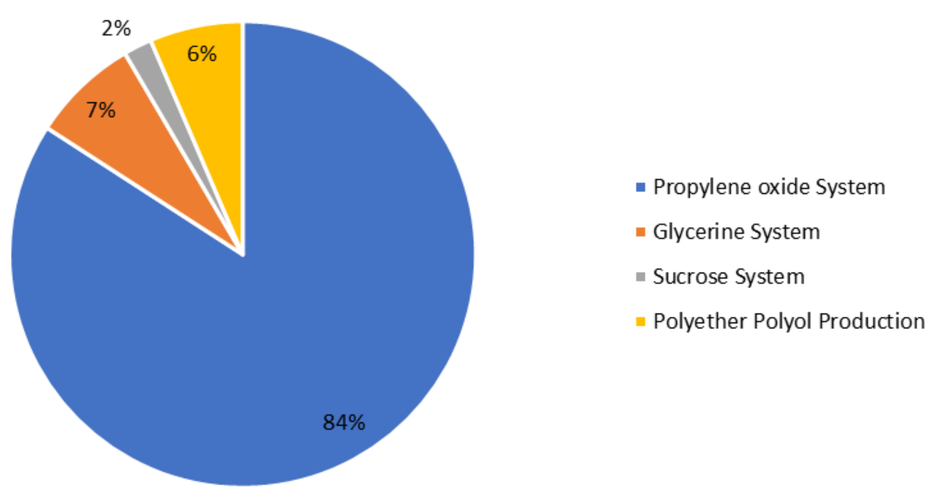

FIGURE 26. GLOBAL WARMING POTENTIAL BY INCOMING MATERIAL SYSTEM AND AVERAGE POLYETHER POLYOL PRODUCTION

Acidification Potential

A description of the Acidification Potential (AP) impact category can be found in Chapter 1. Acidification impacts are typically dominated by fossil fuel combustion emissions, particularly sulfur dioxide (SO2) and nitrogen oxides (NOx). Emissions from combustion of fossil fuels, especially coal, to generate grid electricity is a significant contributor to acidification impacts.

MDI

Emissions from the extraction and processing/refining of natural gas and oil impact the AP category at almost 36 percent of the total AP. This includes extraction and processing of natural gas and oil for both the material production (e.g. as an input to the steam cracker to make pyrolysis gas) and the fuel use. Also, emissions from combustion of fossil fuels, the largest portion from coal to generate grid electricity, are a significant contributor to acidification impacts for the system at 30 percent of the total AP.

Table 25 shows total acidification potential results for the MDI system. Results are shown graphically in Figure 27. In the AP category, 10 percent of the AP is coming from MDI production and about 90 percent comes from the raw and intermediate material unit processes. Of the total AP, two-thirds is coming from the cradle-to-aniline input. As stated previously, much of this comes from the natural gas extraction/processing and the combustion of fuels in the industrial and utility boilers. The carbon monoxide and formaldehyde systems each make up between 9 and 10 percent of the total AP amount, with the other incoming chemicals each accounting for less than 2 percent each of the total AP.

Looking specifically at the phosgene/MDA/MDI unit process, which is 10 percent of the total AP, only 0.1 percent of the total AP comes directly from the associated process emissions of the MDI unit process. The greatest part of the 10 percent AP shown in Table 25 for MDI production comes from the utility boilers used to create electricity (7 percent of the total AP), with smaller amounts from the production of on-site industrial boilers.

TABLE 25. ACIDIFICATION POTENTIAL FOR MDI SYSTEM

	Acidification Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb SO2 eq	***kg SO2 eq***	***%***
Cradle-to-Incoming Materials	6.09	6.09	90%
Phosgene/MDA/MDI Production	0.67	0.67	10%
Total	**6.76**	**6.76**	**100%**

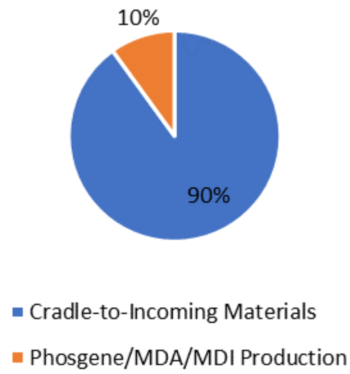

FIGURE 27. PERCENT OF ACIDIFICATION POTENTIAL FOR THE MDI SYSTEM

POLYETHER POLYOL

The combustion emissions of all fuels make up over 40 percent of the total AP throughout the cradle-to-gate production of polyether polyols with coal combustion in utility boilers alone comprising 33 percent of the total AP. The natural gas extraction and processing emissions contributed 39 percent of the total AP results. This includes extraction and processing of natural gas for both the material production (e.g., as an input to the steam cracker to make propylene) and the fuel use.

Table 26 shows total acidification potential results for the polyether polyol system. Results are shown graphically in Figure 28. In the AP category, only 7 percent of the AP is coming from polyether polyol production, while the remaining 93 percent comes from the raw and intermediate material unit processes. Process emissions from the polyether polyol plant produce 4 percent of the gate-to-gate polyether polyol AP amount. Of the rest of the gate-to-gate polyether polyol production, 73 percent comes from electricity (combustion of coal and natural gas), 12 percent from the combustion of natural gas onsite, and 11 percent is produced by incoming transport.

Of the total AP amount, 80 percent of the total AP is created during the production of propylene oxide, which makes up 76 percent of the inputs by mass and includes all of the natural gas extraction/processing/transport amount stated previously. Glycerine and sucrose contribute 6 and 7 percent of the AP total, respectively.

TABLE 26. ACIDIFICATION POTENTIAL FOR POLYETHER POLYOL SYSTEM

	Acidification Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb SO2 eq	*kg SO2 eq*	*%*
Cradle-to-Incoming Materials	7.45	7.45	93%
Polyether Polyol Production	0.57	0.57	7%
Total	**8.02**	**8.02**	**100%**

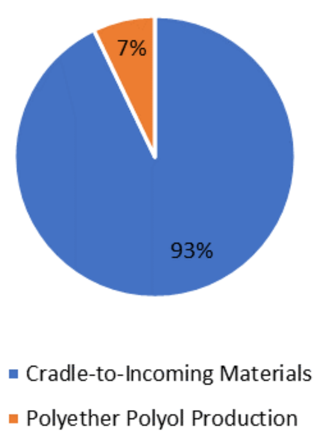

FIGURE 28. PERCENT OF ACIDIFICATION POTENTIAL FOR THE POLYETHER POLYOL SYSTEM

Eutrophication Potential

A description of the Eutrophication Potential (EP) impact category can be found in Chapter 1. Atmospheric emissions of nitrogen oxides (NOx) 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.

MDI

Eutrophication potential (EP) results for MDI and Rigid Polyol are shown in Table 27 and illustrated in Figure 29. The largest portion of the EP results for the MDI are attributed to incoming materials, contributing 97 percent, most of which comes from the aniline system. The cradle-to-aniline extraction comprises 85 percent of the total EP amount. This is due to 1) process emissions released in the manufacture of aniline and from many of the intermediate chemicals created to produce aniline, 2) emissions from the extraction of natural gas used for materials and fuels, and 3) fuel emissions from combustion of fuels in both utility and industrial boilers. The largest portion of this cradle-to-aniline EP amount comes from nitrate compounds and nitrogen oxides released from the nitric acid/nitrobenzene/aniline processes.

The emissions from the phosgene/MDA/MDI unit process comprise 3 percent of the total EP impact results. Only 0.2 percent of the total EP impact comes from process emissions released at the MDI plant. Of this 3 percent associated with the phosgene/MDA/MDI, half represents the combustion of fuels for electricity, while about 40 percent represents the combustion of natural gas on-site in boilers.

TABLE 27. EUTROPHICATION POTENTIAL FOR MDI SYSTEM

	Eutrophication Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb N eq	***kg N eq***	***%***
Cradle-to-Incoming Materials	0.65	0.65	97%
Phosgene/MDA/MDI Production	0.023	0.023	3%
Total	**0.67**	**0.67**	**100%**

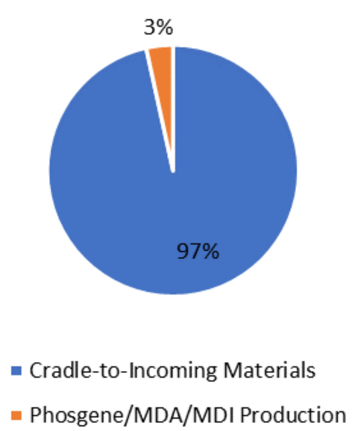

FIGURE 29. PERCENT OF EUTROPHICATION POTENTIAL FOR THE MDI SYSTEM

POLYETHER POLYOL

The greatest portion of the EP amount, almost 80 percent, is attributed to farming of sugarcane and palm kernels. Irrigation is used in these farms which include fertilizer applications. Eutrophication potential (EP) results for the polyether polyol system are shown in Table 28 and illustrated in Figure 30. The production of the raw and intermediate materials used to create polyether polyol contributes 98 percent of the EP results, with 81 percent of the total coming from the farms in the glycerine system and sucrose system. The emissions coming from the cradle-to-gate propylene oxide system comprise 17 percent of the EP impact results. The extraction and processing of natural gas for the materials and fuels used throughout the cradle-to-gate polyether polyol system are 10 percent of the total EP amount.

The gate-to-gate polyether polyol production generates 2 percent of the EP impact as seen in Table 9, with a little less than half of that amount released at the plant site. The emissions released include BOD and COD waterborne emissions, which are normally released from plants with wastewater. Waterborne releases are not always available from plants when the water released is sent to an offsite wastewater treatment plant. The emissions are modeled based on reported amounts in wastewater going to treatment and adjusted for wastewater treatment removal efficiencies (98% removal for BOD and 95% removal for COD). The remaining half of the EP impact for the gate-to-gate polyether polyol comes from emissions released during the creation of electricity and during the combustion of transportation fuels.

TABLE 28. EUTROPHICATION POTENTIAL FOR POLYETHER POLYOL SYSTEM

	Eutrophication Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb N eq	*kg N eq*	*%*
Cradle-to-Incoming Materials	1.65	1.65	98%
Polyether Polyol Production	0.031	0.031	2%
Total	**1.68**	**1.68**	**100%**

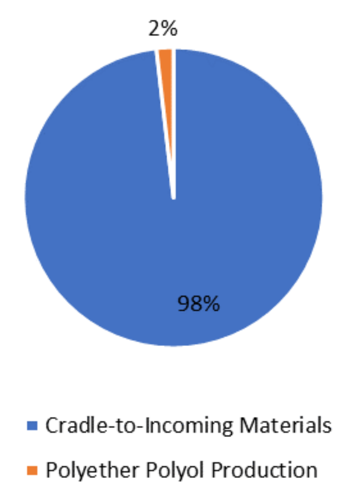

FIGURE 30. PERCENT OF EUTROPHICATION POTENTIAL FOR THE POLYETHER POLYOL SYSTEM

Ozone Depletion Potential

A description of the Ozone Depletion Potential (ODP) impact category can be found in Chapter 1. The main sources of emissions contributing to ODP are minute amounts of tetrachloromethane, HCFCs, and halons are emitted during the extraction of petroleum, which is used as fuel and material in the production of many of the incoming materials, such as olefins.

MDI

Table 29 shows total ODP results for the MDI and Rigid Polyol systems, which are also shown graphically in Figure 31. Ozone depletion results for the MDI system are dominated by the crude oil extraction and refining used to create many of the incoming materials, contributing 91 percent of the ozone depletion impacts associated with incoming materials. The aniline system produces over 95 percent of the ODP, although the manufacture of aniline at the plant only produces 7 percent. The amount of the ODP shown as MDI production is mostly from the small releases of tetrachloromethane from the process. The remaining impact coming from MDI production is for the production of the fuels used in electricity and transport.

TABLE 29. OZONE DEPLETION POTENTIAL FOR MDI SYSTEM

	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	5.9E-06	5.9E-06	98.6%
Phosgene/MDA/MDI Production	8.5E-08	8.5E-08	1.4%
Total	**6.0E-06**	**6.0E-06**	**100%**

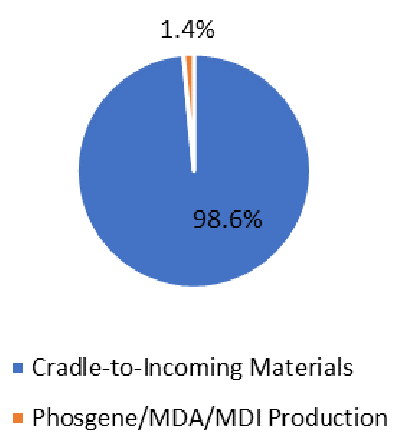

FIGURE 31. PERCENT OF OZONE DEPLETION POTENTIAL FOR THE MDI SYSTEM

POLYETHER POLYOL

Table 30 shows total ODP results for the polyether polyol system, which are also shown graphically in Figure 32. The ODP amount shown in the cradle-to-incoming materials, 66 percent of the total ODP, with emissions from the production of pesticides used during cultivation and harvesting of the palm kernel oil used to produce the glycerine accounting for 38 percent of the total ODP. Much of the remaining ODP for those incoming materials are attributed to the extraction and refining of oil used for both fuels and raw materials, with a small amount from the production of the chlor-alkali required during the production of propylene oxide.

Ozone depletion results for the polyether polyol unit process are dominated by a small amount of refrigerant reported by less than 3 plants. This means there is a probability that this amount may be overstated or understated for any specific plant. Discussions with the plants revealed that refrigerant leaks do happen occasionally but are not common on a regular annual basis.

TABLE 30. OZONE DEPLETION POTENTIAL FOR POLYETHER POLYOL SYSTEM

	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	5.1E-06	5.1E-06	66%
Polyether Polyol Production	2.6E-06	2.6E-06	34%
Total	**7.8E-06**	**7.8E-06**	**100%**

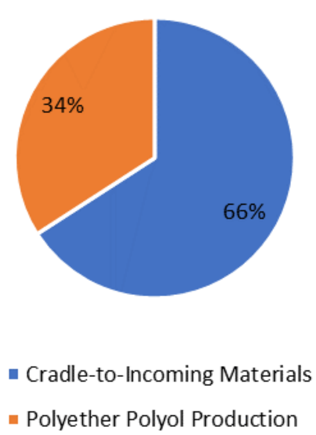

FIGURE 32. PER ENT OF OZONE DEPLETION POTENTIAL FOR THE POLYETHER POLYOL SYSTEM

Photochemical Ozone Creation Potential

A description of the Photochemical Ozone Creation Potential (POCP), also known as smog formation, impact category can be found in Chapter 1. The POCP impact is 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. Normally, NOx makes up the greatest percent (est. 90-95 percent) of the smog formation emissions, with VOCs being the second greatest at around 3-6 percent.

MDI

Smog formation potential results for MDI and Rigid Polyol are shown in Table 31 and Figure 33. Approximately 92 percent of the POCP impacts associated with the MDI system comes from cradle-to-incoming materials. The cradle-to-aniline releases 69 percent of the total impact resulting the POCP; however, only 17 percent of the total is specifically from releases associated with the plant. More than half of the POCP is associated with the extraction/processing/refining of natural gas and oil, which is used throughout all materials and fuels. The POCP impact from the carbon monoxide and formaldehyde systems each comprise 10 percent of the total.

The remaining 8 percent of the POCP impact results is released from the MDI production process. Of that percentage, a little more than half of the POCP for the MDI plant comes from the use of electricity in the plant, which includes the combustion of natural gas and coal at power plants and cogeneration plants. Only 2 percent of the total emissions resulting in the POCP impact results are released at the MDI plant as process emissions. The remaining approximately 40 percent in the MDI production comes from combustion of natural gas or transport of incoming materials.

TABLE 31. PHOTOCHEMICAL OZONE CREATION POTENTIAL FOR MDI SYSTEM

	Photochemical Ozone Creation Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb O3 eq	*kg O3 eq*	*%*
Cradle-to-Incoming Materials	144	144	92%
Phosgene/MDA/MDI Production	12.2	12.2	8%
Total	**156**	**156**	**100%**

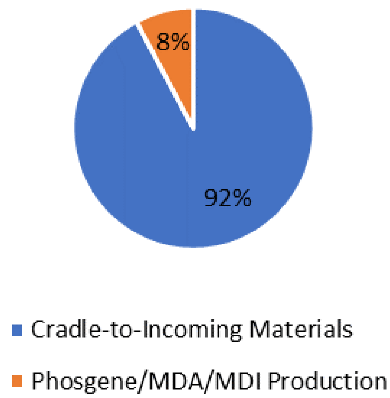

FIGURE 33. PERCENT OF PHOTOCHEMICAL OZONE CREATION POTENTIAL FOR THE MDI SYSTEM

POLYETHER POLYOL

Smog formation potential results for polyether polyol are displayed in Table 32 and illustrated in Figure 34. Approximately 94 percent of the POCP impact results are associated with production of the raw and intermediate materials. The propylene and propylene oxide plants release 10 percent of the total emissions resulting the POCP. Natural gas and oil extraction and processing comprise over half of the total POCP impacts. The combustion of fuels in boilers, equipment, and for transport release emissions that create 32 percent of the POCP total amount.

The remaining 6 percent of the POCP impact is from polyether polyol production. An estimated 0.5 percent of the total emissions resulting in the POCP impact results are released at the polyether polyol plant as process emissions. Of the remaining percentage in the polyether polyol unit process, 55 percent of the POCP comes from generation of electricity used at the plant, with the remainder coming equally from natural gas use at the plant and from the fuels used to transport incoming materials.

TABLE 32. PHOTOCHEMICAL OZONE CREATION POTENTIAL FOR POLYETHER POLYOL SYSTEM

	Photochemical Ozone Creation Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb O3 eq	*kg O3 eq*	*%*
Cradle-to-Incoming Materials	167	167	94%
Polyether Polyol Production	11.0	11.0	6%
Total	**178**	**178**	**100%**

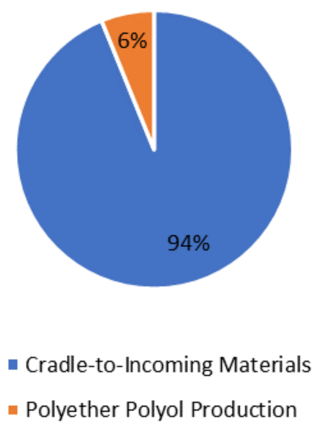

FIGURE 34. PERCENT OF PHOTOCHEMICAL OZONE CREATION POTENTIAL FOR THE POLYETHER POLYOL SYSTEM

CHAPTER 4. PULTRUSION

This chapter describes the pultrusion process, presents the compiled gate-to-gate unit process LCI data for the pultrusion process, and presents LCI and LCIA results for cradle-to-gate production of 1,000 pounds and 1,000 kilograms of pultruded products. The pultrusion data and results provided in this chapter do not represent any specific pultruded product. The inputs and type of pultruded output can vary, and this LCI dataset and LCI/LCIA results represent the average of the data provided by the four companies contributing to this analysis.

GATE-TO-GATE LCI DATA FOR THE PULTRUSION PROCESS

Pultrusion is a processing method that uses thermoset resins or thermoplastic resins to produce a number of complex, high-strength fiber-reinforced polymer composites, such as reinforcing bar and girders used in the construction industry, ladder rail, window lineal, or utility poles.

A pultruded product normally is produced using a thermoset resin, such as VER, UPR, epoxy resin, phenolic resins, or Rigid PUR. A variety of glass fibers (rovings and/or mat) may be used for fiber reinforcement, while potential fillers include limestone, aluminum trihydrate and clay. Additional styrene is sometimes added to VER or UPR by the pultruder to lower the viscosity of the resin system during the pultrusion process. Initiators and other additives may be added as well. The properties of the composite depend on the types and proportions of resins, fillers, and additives incorporated. The input mix for the average pultrusion LCI dataset is not specific to a product, but input data from a variety of pultruders creating many types of products.

Thermoset resins typically start out as liquids or solids with a low melting point that are cured in-situ (i.e., at the point of application undergoing a non-reversible chemical reaction). For this process, fibers are pulled through a liquid resin bath until the fibers are sufficiently impregnated with the resin. Fillers may be added to the mixture to improve the strength and thermal stability of the resin. The coated fibers are then formed to the desired shape and pulled through a heated die to cure the resin. The pultruded composite product exits the die as a continuous profile with the desired-cross sectional shape.

Table 33 presents the complete LCI unit process average data for 1,000 pounds and 1,000 kg of the pultrusion process. Figure 5 in Chapter 1 provides a flow diagram of the average inputs included in the pultrusion process for this analysis. Further information on the data sources of these material inputs are shown in Appendix B.

TABLE 33. LCI UNIT PROCESS AVERAGE DATA FOR THE PULTRUSION PROCESS

	English units		SI Units		
	1,000 lb		1,000 kg		
Material Inputs					
E-glass (representing various types)	741	lb	741	kg	
Vinyl ester resin	45.9	lb	45.9	kg	
Polyurethane polyol	12.1	lb	12.1	kg	
Methylene Diphenyl Diisocyanate (MDI)	19.0	lb	19.0	kg	
Unsaturated Polyester Resin	172	lb	172	kg	
Styrene	8.9	lb	8.9	kg	
Kaolin Clay	22.6	lb	22.6	kg	
Energy					
Process Energy					
Electricity from grid	368	kWh	811	kWh	
Electricity from Renewable Sources	22.9	kWh	50.4	kWh	
Diesel	0.031	gal	0.26	L	
Propane (as LPG)	0.52	gal	4.33	L	
Transportation Energy					
Ocean freighter	397	ton·mi	1,277	tonne·km	
Truck	336	ton·mi	1,082	tonne·km	
	1,000 lb		1,000 kg		
Environmental Emissions					
Atmospheric Emissions					
VOC, unspecified origin	1.02	lb	1.02	kg	
Particulates, unspecified	1.0E-04	lb	1.0E-04	kg	*
Styrene	1.81	lb	1.81	kg	
Methylmethacrylate (MMA)	1.0E-03	lb	1.0E-03	kg	*
Waterborne Releases (none)					
Solid Wastes					
Solid waste, process to landfill	57.9	lb	57.9	kg	
Solid Waste Sold for Recycling or Reuse	17.1	lb	17.1	kg	
Hazardous waste to landfill	4.17	lb	4.17	kg	
Water Consumption	4.1E-05	gal	3.4E-04	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, 2022

LIFE CYCLE INVENTORY AND IMPACT ASSESSMENT RESULTS FOR THE PULTRUSION PROCESS

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

Life cycle inventory results:

- Energy demand
  - Cumulative 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

A description of each of the LCI and LCIA categories can be found in Chapter 1.

Throughout the results sections, the tables and figures break out system results into the following unit processes, for the pultrusion process:

- Cradle-to-incoming materials – includes the raw materials through the production of the incoming materials.
- Pultrusion process – is the gate-to-gate unit process and includes the production of fuels used in the process and transportation of the incoming materials to the production facility.

Some tables and figures include result details for each of the individual input material systems. This split was provided for the main inventory categories, as well as the global warming potential. When considering the individual input materials with the inventory and impact category results, note that this average represents a number of products with varying materials. A discussion of the limitations of these results are available in Chapter 1. These products included a high amount of glass fiber, which is common in pultruded products. The pultruded products include a variety of resins used, including VER, UPR, and PUR; however, no one product would use all the resins included in the average.

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

Energy Demand

Energy Demand has been detailed by renewable and non-renewable energy, as well as by fuel type. A short discussion is provided about the energy of material resource results, which is explained in Chapter 1, as compared to the fuel and process energy results.

Cumulative Energy Demand

Cumulative energy demand results include all renewable and non-renewable energy sources used for process and fuel energy, as well as energy of material resource (also called 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 most of the incoming chemicals (e.g., the energy content of oil and gas used as material feedstocks) to the incoming materials used in the pultrusion products, which is discussed in Chapter 1.

The total energy consumption required to produce pultruded products is 21.4 million Btu per 1,000 pounds or 49.8 GJ per 1,000 kilograms. Table 34 presents the total energy demand for the pultruded composites system. Approximately 79 percent of the total energy demand is attributed to production of incoming materials, while the pultrusion process average contributes 21 percent.

Table 34 also provides details about the non-renewable and renewable energy use within the total energy. 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), as well as use of uranium to generate the share of nuclear energy in the average U.S. kWh. For the pultrusion system, 95 percent of the total energy comes from non-renewable sources. The renewable energy (2.47 GJ/1000 kg) used in the pultrusion system comes from a mix of hydropower, wind, and other renewable sources (geothermal, solar, etc.) from electricity production. Some of the pultrusion companies purchased electricity from renewable sources, as can be seen by the higher amount of renewable energy for the pultrusion processes when compared to that of the total incoming materials.

TABLE 34. TOTAL ENERGY DEMAND FOR THE PULTRUDED PRODUCT SYSTEM

	Basis: 1,000 pounds		
	Total Energy	Non-Renewable Energy	Renewable Energy
	MM Btu	*MM Btu*	*MM Btu*
Cradle-to-Incoming Materials	17.0	16.4	0.60
Pultrusion Process	4.44	3.97	0.47
Total	**21.4**	**20.3**	**1.06**
	Basis: 1,000 kilograms		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	GJ	*GJ*	*GJ*
Cradle-to-Incoming Materials	39.4	38.0	1.39
Pultrusion Process	10.3	9.23	1.08
Total	**49.8**	**47.3**	**2.47**
	Percentage		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	%	*%*	*%*
Cradle-to-Incoming Materials	79%	76%	2.8%
Pultrusion Process	21%	19%	2.2%
Total	**100%**	**95%**	**5.0%**

In Figure 35, a breakout of the total energy, renewable energy, and non-renewable energy is provided, as well as partitioning by individual input materials and the pultrusion process. In this figure, the glass fiber and UPR require the highest amounts of energy. Table 35 provides a tabular presentation of the percentages for each incoming material system and the pultrusion process. Inputs with high amounts normally coincide with having the highest energy demand. This can be seen in the pultrusion system as 39 percent of the total energy demand is required by the glass fiber system. The amount of the UPR resin input is one-fourth of the amount of glass fiber but makes up 25 percent of the total energy; this is due to the feedstock energy stored within the resins systems.

Also in Table 35, the pultrusion process has been broken down into fuel used onsite, electricity, and incoming material transport for an average plant. Electricity used during the pultrusion process accounts for 17 percent of the 21 percent of the energy required for the plant. The incoming material transport makes up most of the remaining energy required at the plant. This amount depends on the plant location and materials inputs, and so may vary depending on the pultrusion company.

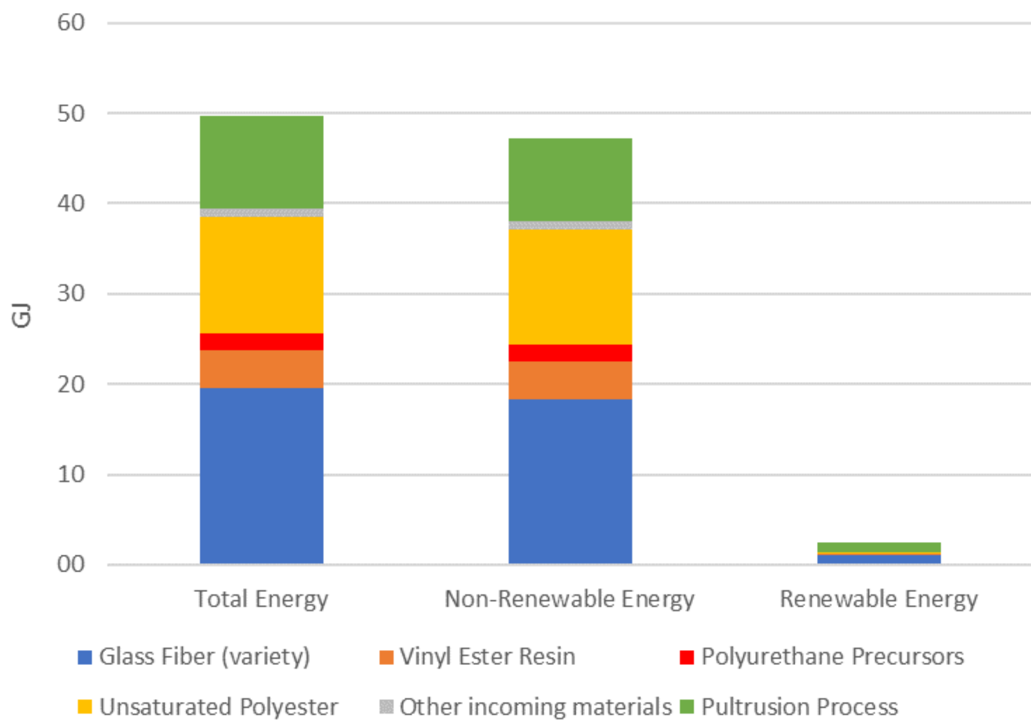

FIGURE 35. TOTAL ENERGY DEMAND FOR THE PULTRUDED PRODUCT SYSTEM

TABLE 35. PERCENT OF TOTAL ENERGY DEMAND BREAKOUT BY INCOMING MATERIALS AND THE PULTRUSION PROCESS

	Percentage		
	Total Energy	Non-Renewable Energy	Renewable Energy
	%	%	%
Incoming Materials Total	**79%**	**80%**	**56%**
Glass Fiber (variety)	*39%*	*39%*	*46%*
Vinyl Ester Resin	*8%*	*9%*	*3%*
Polyurethane Precursors	*4%*	*4%*	*1%*
Unsaturated Polyester	*26%*	*27%*	*6%*
Other incoming materials	*2%*	*2%*	*0.3%*
Pultrusion Process	**21%**	**20%**	**44%**
Fuel use onsite	*0.3%*	*0.3%*	*0.0%*
Electricity	*17%*	*16%*	*44%*
Incoming Material Transport	*4%*	*4%*	*0.2%*
Total	**100%**	**100%**	**100%**

Energy Demand by Fuel Type

The total energy demand by fuel type for pultruded composites is shown in Table 36. Natural gas and petroleum together make up approximately 75 percent of the total energy used. Part of the natural gas and petroleum shown within the incoming materials are due to the material feedstock energy used in the resins. Petroleum-based fuels (e.g., diesel fuel) are the dominant energy source for transportation, which accounts for most of the petroleum shown in the pultrusion process. Coal and nuclear energy each comprise close to 10 percent of the total energy requirements. It can be inferred that electricity is a large part of the energy used since the coal and nuclear are both coming from electricity use.

As shown in Table 36, 60 percent of the energy used (29.9 GJ/49.8 GJ) is from natural gas. Approximately half of that amount is coming from the glass fiber system, and most of the associated natural gas is used for fuel at the glass fiber plant or to create electricity used at the plant. At the pultrusion plant, a third of the energy used (3.5 GJ/10.3 GJ) comes from natural gas. Of the natural gas used at the pultrusion plant, 97 percent is used to create electricity through the grid.

Petroleum comprises approximately 14 percent (7.2 GJ/49.8 GJ) of the total fuel used in the pultrusion system, primarily to produce incoming materials. Of the petroleum used for incoming materials production, more than three-quarters (4.1 GJ/5.3 GJ) is attributed to the production of UPR and VER. This includes the feedstock energy for producing these two resins, of which approximately half is from petroleum and half from natural gas. The petroleum used in the pultrusion process is nearly all associated with the transport of incoming materials.

Solid Waste

Solid waste results in this analysis include only process and fuel-related wastes from raw material acquisition through pultrusion process. Potential process wastes include sludges and residues from chemical reactions, and potential fuel-related wastes include refinery wastes or coal combustion ash. No postconsumer wastes of the products made from pultrusion are included in this analysis as no product is made from the material in the analysis boundaries.

The process solid waste, those wastes produced directly from the production of materials, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. Some wastes that are recycled/reused or land applied are not included as solid wastes, and no credit is given. The categories of disposal type have been provided separately where possible. Solid wastes from fuel combustion (e.g., ash) are assumed to be landfilled.

TABLE 36. ENERGY DEMAND BY FUEL TYPE FOR THE PULTRUSION SYSTEM

	Basis: 1,000 pounds						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	MM Btu	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*
Cradle-to-Incoming Materials	17.0	11.3	2.29	1.46	1.25	0.30	0.30
Pultrusion Process	4.44	1.51	0.81	0.86	0.80	0.27	0.20
Total	**21.4**	**12.9**	**3.10**	**2.32**	**2.05**	**0.57**	**0.50**
	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	39.4	26.4	5.32	3.40	2.92	0.70	0.70
Pultrusion Process	10.3	3.50	1.88	2.00	1.85	0.64	0.46
Total	**49.8**	**29.9**	**7.20**	**5.39**	**4.77**	**1.34**	**1.16**
	Percentage of Total						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	%	*%*	*%*	*%*	*%*	*%*	*%*
Cradle-to-Incoming Materials	79.2%	53.1%	10.7%	6.8%	5.9%	1.4%	1.4%
Pultrusion Process	20.8%	7.0%	3.8%	4.0%	3.7%	1.3%	0.9%
Total	**100%**	**60.1%**	**14.5%**	**10.8%**	**9.6%**	**2.7%**	**2.3%**

Solid waste generation for cradle-to-gate production of pultruded products are shown in Table 37. The solid wastes have been separated into hazardous and non-hazardous waste categories, fate of the solid waste, and by the cradle-to-incoming materials and the pultrusion process. Less than 1 percent of the total solid waste is considered hazardous waste with most of that hazardous waste going to a hazardous waste landfill, while small amounts of the remaining incinerated either with or without energy capture. The remaining 99 percent of the solid waste is non-hazardous. Almost all of the non-hazardous solid waste is landfilled, while small amounts of the remainder incinerated either with or without energy capture.

Figure 36 shows the percent of total solid wastes separated by the cradle-to-incoming materials and the pultrusion process. The glass fiber system input to pultrusion produces the highest amounts of solid waste at 72 percent of the total solid wastes. There are many inputs to glass fiber that are minerals; these inputs to glass fiber make up half the solid waste that it creates, while the other half is associated with the glass fiber plant. Within all the input material systems, much of the solid wastes (17 percent) are coming from the production and combustion of coal used to create electricity. The resins inputs as a total create approximately 5 percent of the total solid waste.

TABLE 37. TOTAL SOLID WASTES BY DISPOSAL FATE FOR THE PULTRUSION SYSTEM

	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	398	0.12	0.17	0.0030	0.30	0.36	0.95	396	397
Pultrusion Process	96.8	0	0	4.20	4.20	0	0	92.6	92.6
Total	**494**	**0.12**	**0.17**	**4.20**	**4.50**	**0.36**	**0.95**	**489**	**490**
	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	398	0.12	0.17	0.0030	0.30	0.36	0.95	396	397
Pultrusion Process	96.8	0	0	4.20	4.20	0	0	92.6	92.6
Total	**494**	**0.12**	**0.17**	**4.20**	**4.50**	**0.36**	**0.95**	**489**	**490**
	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	80%	0.02%	0.04%	0.00%	0.06%	0.07%	0.19%	80%	80%
Pultrusion Process	20%	0%	0%	0.85%	0.85%	0%	0%	19%	19%
Total	**100%**	**0.02%**	**0.04%**	**0.85%**	**0.91%**	**0.07%**	**0.19%**	**99%**	**99%**

As shown in Figure 36, only 20 percent of the total solid waste is created during the pultrusion process. Within the pultrusion process, more than half of the solid waste is created as a process waste at the plant. This includes product trim/scrap, incoming packaging waste, filters and other miscellaneous wastes. The largest portion of this is product trim/scrap which will vary among product types. The remaining solid waste at the plant mostly comes from the combustion of coal for electricity.

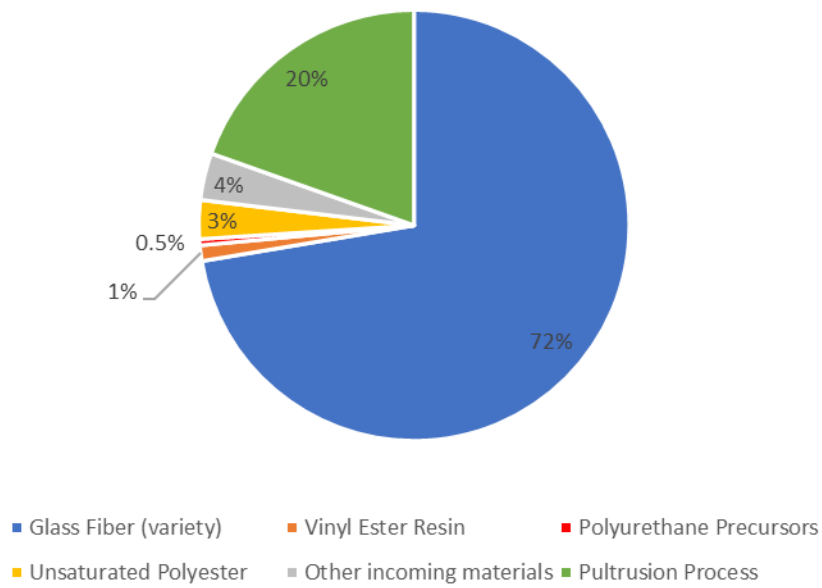

FIGURE 36. PERCENTAGE OF TOTAL SOLID WASTES BY INCOMING MATERIAL AND THE PULTRUSION PROCESS

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.

Consumptive water use for the pultrusion system is presented in Table 38 and Figure 37. Both the table and figure have been split out by incoming material and the pultrusion process. The amount of water consumed to produce 1,000 kilograms of pultruded products is 18,533 liter, or 2,223 gallons per 1,000 pounds.

Almost 60 percent of the water is consumed during the production of electricity used during the manufacture all of the incoming materials and the pultrusion process. The largest amount of water consumption comes from the cradle-to-incoming materials (69 percent), specifically the cradle-to-glass fiber, which produces over 50 percent of the total. The glass fiber system water consumption comes from water used from hydropower to create electricity as well as from the glass fiber process itself. The resin systems all consume between 4 and 8 percent of the total water.

Water consumed at the pultrusion facility itself comprises 31 percent of total cradle-to-gate demand. The plant itself consumes very little water at less than 0.1 percent of the water consumptions shown for the pultrusion process within Table 38. Almost all the water consumption for the pultrusion process comes from the use of hydropower to produce electricity used in the process.

TABLE 38. WATER CONSUMPTION FOR THE PULTRUSION SYSTEM

	Total Water Consumption		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	Gallons	***Liters***	***%***
Glass Fiber (variety)	1,177	9,824	53%
Vinyl Ester Resin	96	803	4%
Polyurethane Precursors	86	720	4%
Unsaturated Polyester	170	1,415	8%
Other incoming materials	11	93	0.5%
Pultrusion Process	683	5,696	31%
Total	**2,223**	**18,553**	**100%**

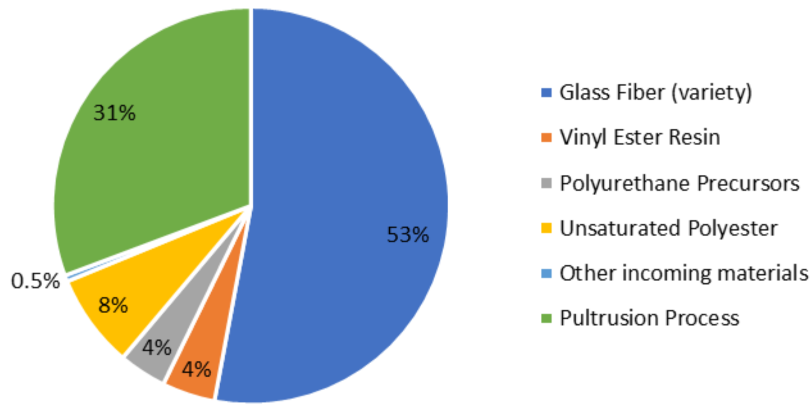

FIGURE 37. WATER CONSUMPTION BY INCOMING MATERIALS AND PULTRUSION PROCESS

Global Warming Potential

The primary atmospheric emissions reported in this analysis that contribute over 99 percent of the total global warming potential (GWP) are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. Other contributors include some HCFCs and other greenhouse gases, but these contribute less than 1 percent of the total shown. Greenhouse gas emissions are mainly from combustion. In the primary data collected for many of the intermediate chemicals used in pultrusion, combustion emissions from flare or another type of emissions control 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 use of the emissions control. Data providers were asked to estimate percentages of greenhouse gases from flare from that of the combustion of fuels. Further discussion of the impact category can be found in Chapter 1.

In Table 39 and Figure 38, the life cycle GWP results for the pultrusion system are displayed by input material system and the pultrusion process. In the pultrusion system, a correlation between energy use and greenhouse gas emissions, most of which are from combustion, can be seen. The glass fiber system does have a somewhat higher percentage of the total GWP as compared to that of the total energy, while the UPR and other resins have a lower percentage. This is due to the feedstock energy included in the resins as inherent energy which is not combusted and so does not produce greenhouse gas emissions.

Of the total GWP attributed to the pultrusion unit process, 79 percent is attributed to emissions from the incoming materials and the remaining amount is associated with the pultrusion process. Approximately 62 percent of the GWP is created by both industrial and utility boiler emissions throughout the production of incoming materials and the pultrusion.

The glass fiber unit process releases some greenhouse gas emissions during the burning of limestone and other minerals to create the material.

The pultrusion process accounts for 21 percent of the total GWP. Of this amount, three quarters come from combustion of fuels at utility boilers to create electricity. The remaining 25 percent comes from the burning of fuels for transport of the incoming materials to the pultrusion plant.

TABLE 39. GLOBAL WARMING POTENTIAL FOR THE PULTRUSION SYSTEM

	Global Warming Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb CO2 eq	***kg CO2 eq***	***%***
Glass Fiber (variety)	1,416	1,416	52%
Vinyl Ester Resin	162	162	6%
Polyurethane Precursors	73	73	3%
Unsaturated Polyester	453	453	17%
Other incoming materials	30	30	1%
Pultrusion Process	575	575	21%
Total	**2,708**	**2,708**	**100%**

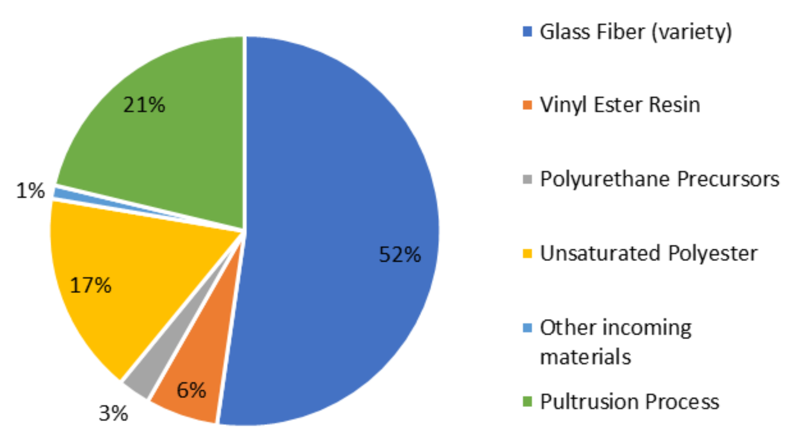

FIGURE 38. PERCENT OF GLOBAL WARMING POTENTIALBY INCOMING MATERIALS AND PULTRUSION PROCESS

Acidification Potential

A description of the Acidification Potential (AP) impact category can be found in Chapter 1. Acidification impacts are typically dominated by fossil fuel combustion emissions, particularly sulfur dioxide (SO2) and nitrogen oxides (NOx). Emissions from combustion of fossil fuels, especially coal, to generate grid electricity is a significant contributor to acidification impacts. The combustion of coal alone for electricity makes up almost 50 percent of the total AP, while combustion of all fuels increases the amount to 57 percent of the total. Also, emissions from oil and natural gas extraction and processing/refining and transport fuel combustion each create 17 percent of the total AP category.

Table 40 presents the AP results for the pultrusion system, which shows that 67 percent of the total AP comes from the incoming material systems, while the remaining 33 percent comes from pultrusion process. Figure 39 provides the results detailing the AP by percent of incoming material and the pultrusion process. Considering the incoming material systems, nearly half of the total AP is coming from the cradle-to-gate production of glass fibers. Much of this amount comes from the combustion of fuels in the industrial and utility boilers. The three resin systems make up almost 20 percent of the total AP as a whole due to the combustion of fuels needed as well as the transport and oil and gas extraction and processing/refining.

Looking specifically at the pultrusion process, which is 33 percent to the total AP, the greatest portion of the AP amount comes from the utility boilers used to create electricity, with smaller amounts coming from transportation processes. No process emissions are released at the pultrusion process that affect the AP total.

TABLE 40. ACIDIFICATION POTENTIAL FOR THE PULTRUSION SYSTEM

	Acidification Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb SO2 eq	***kg SO2 eq***	***%***
Cradle-to-Incoming Materials	6.16	6.16	67%
Pultrusion Process	3.08	3.08	33%
Total	**9.24**	**9.24**	**100%**

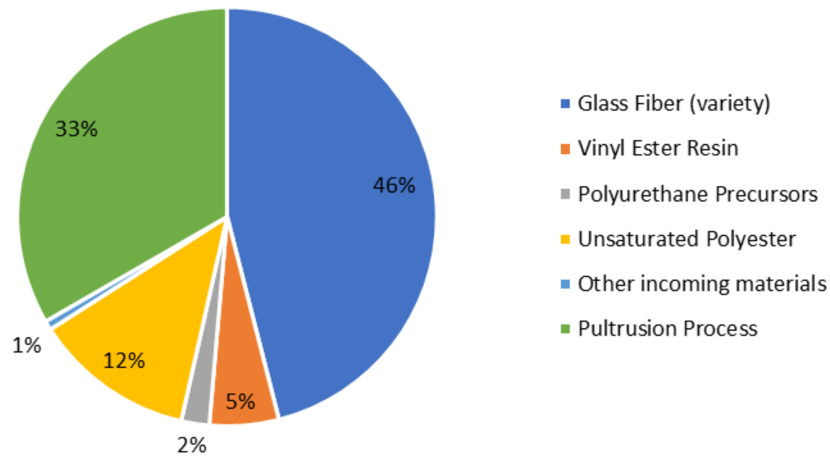

FIGURE 39. PERCENT OF ACIDIFICATION POTENTIAL BY INCOMING MATERIAL AND FOR PULTRUSION PROCESS

Eutrophication Potential

A description of the Eutrophication Potential (EP) impact category can be found in Chapter 1. Atmospheric emissions of nitrogen oxides (NOx) 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.

Table 41 presents the EP results for the pultrusion system. In the EP category, 85 percent of the total EP comes from the incoming materials. Figure 40 provides the results detailing the EP by percent of incoming material and the pultrusion process. The greatest portion (over 50 percent) of the EP from incoming material is due to process emissions released during the manufacture of many of the intermediate chemicals as well as the incoming material production itself. The greatest portion of the total EP for pultruded composites comes from the cradle-to-gate manufacture of UPR, which makes up 39 percent of the total EP. This is due to emission releases during the production of the intermediate chemicals, propylene glycol and maleic anhydride. The cradle-to-gate manufacture of VER and E-glass make up approximately 20 percent each of the total EP.

Looking specifically at pultrusion process, no process emissions are released at the pultrusion process that affect the EP total. Half of the EP amount associated with the pultrusion process comes from combustion of fuels for electricity production, while the remaining comes from the production of fuels for transport.

TABLE 41. EUTROPHICATION POTENTIAL FOR PULTRUSION SYSTEM

	Eutrophication Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb N eq	*kg N eq*	*%*
Cradle-to-Incoming Materials	0.51	0.51	85%
Pultrusion Process	0.091	0.091	15%
Total	**0.61**	**0.61**	**100%**

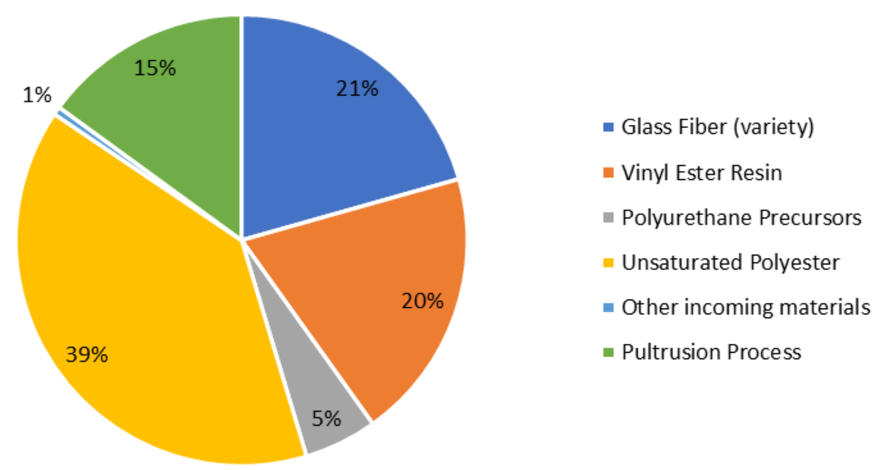

FIGURE 40. PERCENT OF EUTROPHICATION POTENTIAL BY INCOMING MATERIAL AND PULTRUSION PROCESS

Ozone Depletion Potential

A description of the Ozone Depletion Potential (ODP) impact category can be found in Chapter 1. The main sources of emissions contributing to ODP are minute amounts of tetrachloromethane, HCFCs, and halons are emitted during the extraction of petroleum, which is used as fuel and material in the production of many of the incoming materials, such as benzene and olefins.

Table 42 shows the total Ozone Depletion Potential results for the pultrusion system. ODP results split by cradle-to-individual incoming material and the pultrusion process are shown graphically in Figure 41. Ozone depletion results for the pultrusion system are dominated by the incoming material systems, which account for 94 percent of the total. Almost three-quarters of the total ODP amount is coming from the UPR system. Much of this is attributed to an intermediate chemical in the UPR system that included refrigerant leaks. This type of release does not happen every year at chemical plants, the ODP amount could vary greatly from year to year depending on this type of uncontrolled release.

ODP results for the pultrusion process specifically are associated with the extraction and refining of oil used to make fuels for transport of incoming materials. No process emissions were released at the pultrusion plants.

Table 42. Ozone Depletion Potential for the Pultrusion System

	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	94%
Pultrusion Process	4.3E-07	4.3E-07	6%
Total	**7.6E-06**	**7.6E-06**	**100%**

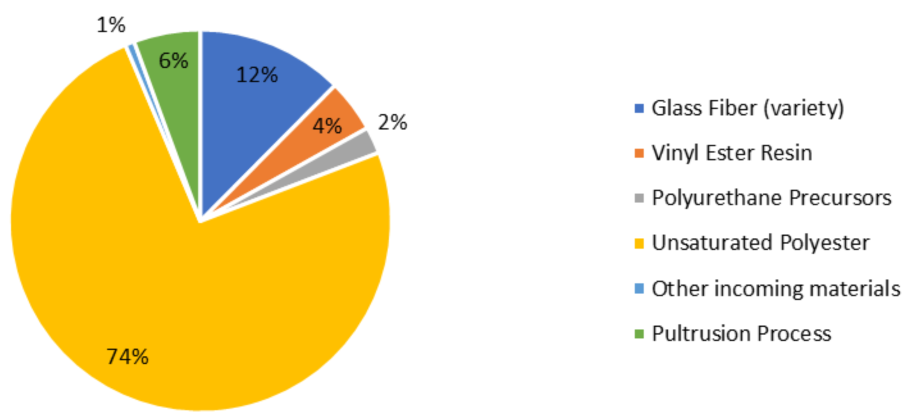

Figure 41. Percent of Ozone Depletion Potential by Incoming Material and the Pultrusion Process

Photochemical Ozone Creation Potential

A description of the Photochemical Ozone Creation Potential (POCP), also known as smog formation, impact category can be found in Chapter 1. POCP are generally dominated by emissions associated with fuel combustion, so that impacts are higher for life cycle stages and components that have higher process fuel and transportation fuel requirements. In this case, NOx makes up 92 percent of the smog formation emissions, with VOCs consisting of 5 percent.

Table 43 shows total photochemical ozone creation potential results for the pultrusion system. POCP results split by cradle-to-individual incoming material and the pultrusion process are shown graphically in Figure 42. Approximately 66 percent of the POCP impact comes from the cradle-to-incoming materials. The cradle-to-gate manufacture of glass fiber releases 40 percent of the total impact resulting from POCP; much of this comes from the combustion of fuels in industrial and utility boilers. The UPR material system makes up 16 percent of the total POCP with much of it coming from the extraction and processing/refining of natural gas and oil used for both material and fuel.

The pultrusion process contributes approximately 34 percent to the total POCP. A little more than 40 percent of this POCP amount comes from the use of electricity at the pultrusion facility, which includes the combustion of coal and natural gas in industrial and utility boilers. The incoming material transport also comprises little more than 40 percent of the POCP associated with the pultrusion process. The pultrusion process itself does release emissions accounting for a little more than 10 percent of the POCP amount from the pultrusion unit process.

TABLE 43. PHOTOCHEMICAL OZONE CREATION POTENTIAL FOR THE PULTRUSION SYSTEM

	Photochemical Ozone Creation Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb O3 eq	*kg O3 eq*	*%*
Cradle-to-Incoming Materials	110	110	66%
Pultrusion Process	57.2	57.2	34%
Total	**167**	**167**	**100%**

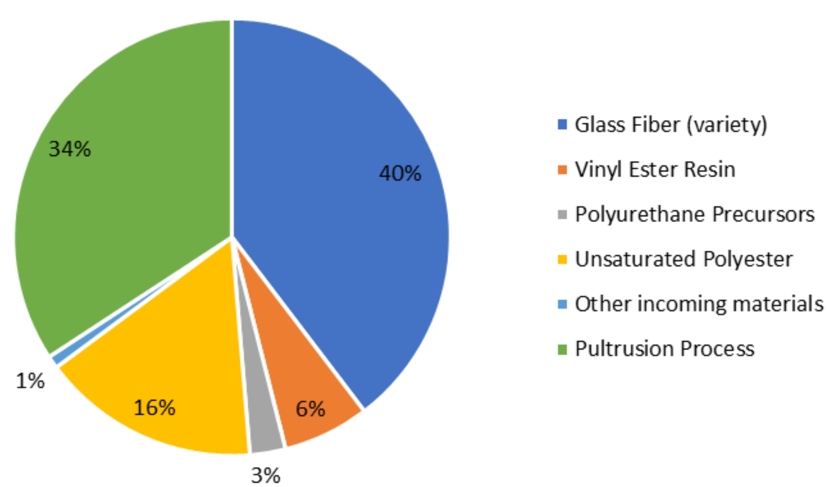

FIGURE 42. PERCENT OF PHOTOCHEMICAL OZONE CREATION POTENTIAL BY INCOMING MATERIAL AND PULTRUSION PROCESS

APPENDIX A. CRADLE-TO-GATE LCI EMISSIONS DATA TABLES

This appendix section details the quantitative cradle-to-gate LCI atmospheric and waterborne emissions results for each of the materials and the pultrusion process in this analysis. These tables are provided in this appendix due to their length.

TABLE 44. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF VINYL ESTER RESIN

	1 kg	
Environmental Emissions		
Atmospheric Emissions		
4-Methyl-2-pentanone	1.08E-07	kg
Acetaldehyde	1.05E-06	kg
Acetone	2.07E-04	kg
Acrolein	8.56E-07	kg
Aldehydes, unspecified	1.75E-07	kg
Ammonia	8.53E-06	kg
Ammonium chloride	5.16E-07	kg
Argon-41	2.63E-07	Bq
Arsenic	3.99E-08	kg
Benzene	4.97E-04	kg
Benzene, 1,2,4-trimethyl-	1.12E-07	kg
Benzene, ethyl-	1.04E-06	kg
Butadiene	2.08E-07	kg
Butane	1.61E-06	kg
Cadmium	2.00E-08	kg
Carbon-14	2.01E-06	Bq
Carbon dioxide	3.21E+00	kg
Carbon disulfide	2.30E-08	kg
Carbon monoxide	2.43E-03	kg
Carbonyl sulfide	1.63E-07	kg
Chlorine	1.38E-05	kg
Chromium	4.12E-08	kg
Cobalt	2.64E-08	kg
Cresol	1.33E-08	kg
Cumene	5.87E-04	kg
Cyanamide	3.73E-07	kg
Cyanide	2.62E-08	kg
Cyclohexane	1.49E-07	kg
Diethanolamine	2.93E-08	kg
Ethene	3.25E-07	kg
Ethene, tetrachloro-	1.78E-08	kg
Fluoride	4.79E-07	kg
Formaldehyde	9.26E-06	kg
Hexane	1.58E-06	kg
Hydrocarbons, unspecified	3.47E-06	kg
Hydrogen	2.91E-08	kg
Hydrogen-3, Tritium	1.17E-05	Bq
Hydrogen chloride	9.63E-05	kg

TABLE 44. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF VINYL ESTER RESIN (CONTINUED)

	1 kg	
Atmospheric Emissions		
Hydrogen cyanide	1.17E-06	kg
Hydrogen fluoride	1.21E-05	kg
Hydrogen sulfide	5.88E-07	kg
Iodine-131	1.04E-07	Bq
Kerosene	2.47E-07	kg
Krypton-85	8.23E-07	Bq
Krypton-85m	3.40E-08	Bq
Krypton-87	1.46E-08	Bq
Krypton-88	1.39E-08	Bq
Lead	8.19E-08	kg
Lead-210	1.12E-08	Bq
Magnesium	9.19E-07	kg
Manganese	5.58E-08	kg
Mercaptans, unspecified	2.27E-06	kg
Mercury	2.39E-08	kg
Methane	9.42E-03	kg
Methane, dichloro-, HCC-30	5.93E-08	kg
Methanol	1.23E-06	kg
Methyl methacrylate	1.00E-06	kg
Naphthalene	1.12E-07	kg
Nickel	3.06E-07	kg
Nitrogen oxides	8.69E-03	kg
Nitrogen, atmospheric	2.51E-02	kg
Nitrous oxide	1.61E-04	kg
Noble gases, radioactive, unspecified	1.97E-02	Bq
Organic substances, unspecified	6.74E-07	kg
Ozone	1.97E-08	kg
PAH, polycyclic aromatic hydrocarbons	1.29E-08	kg
Particulates, < 10 um	2.24E-04	kg
Particulates, < 2.5 um	2.32E-04	kg
Particulates, > 2.5 um, and < 10um	7.09E-05	kg
Particulates, unspecified	5.09E-04	kg
Pentane, 2,2,4-trimethyl-	1.73E-07	kg
Phenol	6.70E-04	kg
Phosphorus	1.71E-08	kg
Polonium-210	1.97E-08	Bq
Propene	2.61E-04	kg
Radioactive species, unspecified	4.14E+03	Bq

TABLE 44. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF VINYL ESTER RESIN (CONTINUED)

	1 kg	
Atmospheric Emissions		
Radium-226	1.18E-08	Bq
Radon-220	1.12E-07	Bq
Radon-222	8.65E-04	Bq
Selenium	1.12E-07	kg
Styrene	1.38E-08	kg
Sulfur dioxide	2.79E-03	kg
Sulfur oxides	1.73E-03	kg
Sulfur trioxide	1.76E-07	kg
Sulfuric acid	1.28E-06	kg
t-Butyl methyl ether	1.69E-08	kg
TOC, Total Organic Carbon	8.80E-06	kg
Toluene	8.75E-06	kg
Uranium alpha	1.51E-08	Bq
VOC, volatile organic compounds	2.82E-03	kg
Xenon-131m	6.64E-08	Bq
Xenon-133	2.08E-06	Bq
Xenon-135	8.56E-07	Bq
Xenon-135m	5.01E-07	Bq
Xenon-138	8.13E-08	Bq
Xylene	2.91E-06	kg
Zinc compounds	1.49E-08	kg
Waterborne Releases		
1-Butanol	8.04E-07	kg
Acetaldehyde	1.29E-06	kg
Acetic acid	3.72E-05	kg
Acetone	1.01E-03	kg
Acidity, unspecified	2.38E-07	kg
Aluminium	4.05E-06	kg
Ammonia	7.81E-07	kg
Ammonium, ion	1.10E-07	kg
AOX, Adsorbable Organic Halogen as Cl	4.40E-05	kg
Barium	1.77E-04	kg
Benzene	1.16E-03	kg
Benzene, ethyl-	9.22E-07	kg
Bicarbonate, ion	1.25E-03	kg
Biphenyl	5.58E-07	kg
BOD5, Biological Oxygen Demand	2.14E-02	kg

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TABLE 44. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF VINYL ESTER RESIN (CONTINUED)

	1 kg	
Waterborne Releases		
Boron	9.03E-07	kg
Butadiene	5.58E-07	kg
Butyl acetate	1.05E-06	kg
Calcium	1.38E-04	kg
Cesium-137	3.82E-07	Bq
Chloride	9.10E-02	kg
COD, Chemical Oxygen Demand	2.18E-02	kg
Copper	1.03E-07	kg
Cumene	1.56E-03	kg
Dimethyl phthalate	5.58E-08	kg
Dissolved solids	1.27E-02	kg
DOC, Dissolved Organic Carbon	6.55E-03	kg
Ethanol	1.85E-06	kg
Ethene	5.58E-06	kg
Ethylene glycol	5.71E-07	kg
Fluoride	1.79E-06	kg
Hydrocarbons, unspecified	1.28E-05	kg
Hydrogen-3, Tritium	8.76E-04	Bq
Iron	8.61E-06	kg
Isoprene	5.61E-08	kg
Lead	1.42E-08	kg
Magnesium	2.33E-05	kg
Manganese	1.14E-05	kg
Methanol	1.31E-06	kg
Nitrate	3.19E-08	kg
Nitrate compounds	6.39E-06	kg
Nitrogen	6.46E-06	kg
Oils, unspecified	1.06E-05	kg
Organic substances, unspecified	2.41E-07	kg
Phenol	3.28E-03	kg
Phosphate	1.48E-06	kg
Phosphorus, total	7.86E-08	kg
Potassium	3.86E-05	kg
Propene	6.24E-04	kg
Propylene glycol	5.58E-07	kg
Radioactive species, Nuclides, unspecified	1.60E+01	Bq

TABLE 44. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF VINYL ESTER RESIN (CONTINUED)

	1 kg	
Waterborne Releases		
Radium-224	1.51E-06	Bq
Radium-226	5.61E-06	Bq
Radium-228	3.03E-06	Bq
Selenium	3.89E-08	kg
Silicate	3.90E-07	kg
Sodium	5.84E-02	kg
Strontium-90	2.88E-06	Bq
Styrene	5.95E-06	kg
Sulfate	9.52E-04	kg
Sulfide	5.55E-07	kg
Sulfuric acid	2.63E-07	kg
Suspended solids, unspecified	1.10E-04	kg
Thorium-228	6.06E-06	Bq
Thorium-230	6.97E-07	Bq
TOC, Total Organic Carbon	6.63E-03	kg
Toluene	5.58E-06	kg
Uranium-235	1.01E-08	Bq
Uranium-238	1.94E-08	Bq
Uranium alpha	2.94E-07	Bq
Xylene	5.61E-07	kg
Zinc	1.76E-07	kg
Zinc compounds	1.44E-08	kg

TABLE 45. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF MDI

	1 kg	
Environmental Emissions		
Atmospheric Emissions		
4-Methyl-2-pentanone	1.14E-07	kg
4,4'-Methylenedianiline (MDA)	1.00E-08	kg
Acetaldehyde	1.10E-06	kg
Acrolein	9.07E-07	kg
Aldehydes, unspecified	1.24E-06	kg
Ammonia	1.77E-04	kg
Ammonium chloride	2.47E-07	kg
Aniline	1.01E-07	kg
Arsenic	1.97E-08	kg
Benzene	1.31E-05	kg
Benzene, 1,2,4-trimethyl-	1.19E-07	kg
Benzene, chloro-	1.04E-07	kg
Benzene, ethyl-	1.10E-06	kg
Butadiene	2.21E-07	kg
Carbon dioxide	2.27E+00	kg
Carbon disulfide	2.30E-08	kg
Carbon monoxide	1.76E-03	kg
Carbonyl sulfide	1.73E-07	kg
Chlorine	3.26E-06	kg
Chromium	1.72E-08	kg
Cobalt	2.29E-08	kg
Cresol	1.41E-08	kg
Cumene	6.22E-08	kg
Cyanamide	3.96E-07	kg
Cyclohexane	1.58E-07	kg
Diethanolamine	3.12E-08	kg
Dimethyl ether	1.68E-05	kg
Ethene	3.45E-07	kg
Ethene, tetrachloro-	1.65E-08	kg
Formaldehyde	9.02E-06	kg
Hexane	1.68E-06	kg
Hydrocarbons, unspecified	1.91E-06	kg
Hydrogen chloride	4.78E-05	kg
Hydrogen cyanide	1.24E-06	kg
Hydrogen fluoride	5.27E-06	kg

TABLE 45. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF MDI (CONTINUED)

	1 kg	
Atmospheric Emissions		
Hydrogen sulfide	6.24E-07	kg
Kerosene	1.18E-07	kg
Lead	2.56E-08	kg
Magnesium	3.85E-07	kg
Manganese	3.12E-08	kg
Methane	5.67E-03	kg
Methane, chlorodifluoro-, HCFC-22	1.44E-08	kg
Methane, dichloro-, HCC-30	4.74E-08	kg
Methanol	5.19E-06	kg
Naphthalene	1.13E-07	kg
Nickel	3.02E-07	kg
Nitrogen dioxide	2.41E-06	kg
Nitrogen oxides	5.88E-03	kg
Nitrous oxide	3.25E-04	kg
Organic substances, unspecified	1.77E-04	kg
Oxygen	3.23E-02	kg
Ozone	2.09E-08	kg
PAH, polycyclic aromatic hydrocarbons	1.39E-08	kg
Particulates, < 10 um	1.45E-04	kg
Particulates, < 2.5 um	1.74E-04	kg
Particulates, > 2.5 um, and < 10um	2.93E-05	kg
Particulates, unspecified	1.52E-04	kg
Pentane, 2,2,4-trimethyl-	1.84E-07	kg
Phenol	6.04E-08	kg
Phosgene	1.00E-08	kg
Phosphorus	1.82E-08	kg
Propene	8.82E-07	kg
Radioactive species, unspecified	1.98E+03	Bq
Selenium	4.83E-08	kg
Styrene	1.44E-08	kg
Sulfur dioxide	1.26E-03	kg
Sulfur oxides	9.99E-04	kg
Sulfur trioxide	2.27E-08	kg
Sulfuric acid	1.36E-06	kg
t-Butyl methyl ether	1.75E-08	kg
TOC, Total Organic Carbon	2.06E-04	kg
Toluene	9.27E-06	kg
VOC, volatile organic compounds	2.69E-03	kg
Xylene	3.09E-06	kg
Zinc compounds	1.58E-08	kg

TABLE 45. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF MDI (CONTINUED)

	1 kg	
Waterborne Releases		
4,4'-Diaminodiphenylmethane	1.00E-08	kg
Acidity, unspecified	2.53E-07	kg
Aluminium	1.94E-06	kg
Ammonia	1.05E-05	kg
Ammonium, ion	5.28E-08	kg
Aniline	8.17E-05	kg
Barium	1.37E-04	kg
Benzene	2.32E-06	kg
Benzene, chloro-	1.04E-08	kg
Benzene, ethyl-	2.32E-07	kg
Bicarbonate, ion	9.72E-04	kg
Biphenyl	2.32E-07	kg
BOD5, Biological Oxygen Demand	4.45E-04	kg
Boron	7.00E-07	kg
Butadiene	2.32E-07	kg
Calcium	1.07E-04	kg
Chloride	1.46E-03	kg
COD, Chemical Oxygen Demand	9.15E-04	kg
Copper	5.11E-08	kg
Dimethyl phthalate	2.32E-08	kg
Dissolved solids	9.89E-03	kg
Ethene	2.32E-06	kg
Ethylene glycol	2.46E-07	kg
Fluoride	8.61E-07	kg
Hydrocarbons, unspecified	9.92E-06	kg
Iron	4.21E-06	kg
Isoprene	2.35E-08	kg
Magnesium	1.81E-05	kg
Manganese	8.12E-06	kg
Methanol	1.21E-07	kg
Nitrate	8.16E-05	kg
Nitrate compounds	8.23E-04	kg
Nitrobenzene	8.16E-05	kg
Nitrogen	1.18E-05	kg
Oils, unspecified	2.18E-05	kg

TABLE 45. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF MDI (CONTINUED)

	1 kg	
Waterborne Releases		
Phenol	1.30E-07	kg
Phosphate	1.57E-06	kg
Phosphorus, total	6.09E-08	kg
Potassium	9.25E-06	kg
Propylene glycol	2.32E-07	kg
Radioactive species, Nuclides, unspecified	7.67E+00	Bq
Selenium	1.89E-08	kg
Silicate	3.03E-07	kg
Sodium	4.59E-04	kg
Sodium chloride	3.50E-03	kg
Styrene	2.32E-06	kg
Sulfate	6.73E-04	kg
Sulfide	7.24E-07	kg
Sulfuric acid	3.38E-08	kg
Suspended solids, unspecified	1.22E-04	kg
TOC, Total Organic Carbon	7.82E-05	kg
Toluene	2.32E-06	kg
Xylene	2.35E-07	kg
Zinc	8.34E-08	kg
Zinc compounds	1.53E-08	kg

TABLE 46. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF POLYETHER POLYOL FOR RIGID POLYURETHANE

	1 kg	
Environmental Emissions		
Atmospheric Emissions		
1-Propanol	1.69E-08	kg
2-Methyl-4-chlorophenoxyacetic acid	5.14E-08	kg
4-Methyl-2-pentanone	2.57E-08	kg
Acephate	3.95E-08	kg
Acetaldehyde	3.37E-07	kg
Acetic acid	3.14E-06	kg
Acetone	1.71E-08	kg
Aclonifen	2.52E-07	kg
Acrolein	2.31E-07	kg
Actinides, radioactive, unspecified	3.20E-07	Bq
Aerosols, radioactive, unspecified	7.95E-06	Bq
Aldehydes, unspecified	1.39E-06	kg
Aluminium	5.30E-08	kg
Ammonia	2.52E-04	kg
Ammonium chloride	4.50E-07	kg
Antimony-124	3.24E-08	Bq
Argon-41	4.99E-02	Bq
Arsenic	3.06E-08	kg
Atrazine	1.99E-07	kg
Azoxystrobin	1.04E-08	kg
Barium-140	3.29E-08	Bq
Benzene	3.71E-06	kg
Benzene, 1,2-dichloro-	1.08E-08	kg
Benzene, 1,2,4-trimethyl-	3.31E-08	kg
Benzene, ethyl-	1.06E-03	kg
Bifenthrin	3.52E-08	kg
Boron	1.57E-08	kg
Butadiene	5.69E-08	kg
Butane	4.35E-07	kg
Butene	2.20E-08	kg
Cadmium	1.83E-08	kg
Captan	6.09E-08	kg
Carbaryl	1.17E-08	kg
Carbon-14	5.45E-02	Bq
Carbon dioxide	2.36E+00	kg
Carbon dioxide, biogenic	4.59E-05	kg
Carbon disulfide	1.41E-08	kg
Carbon monoxide	1.83E-03	kg
Carbon monoxide, biogenic	4.37E-03	kg

TABLE 46. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF POLYETHER POLYOL FOR RIGID POLYURETHANE (CONTINUED)

	1 kg	
Atmospheric Emissions		
Carbonyl sulfide	4.06E-08	kg
Cesium-134	5.62E-06	Bq
Cesium-137	1.15E-05	Bq
Chloridazon	1.42E-07	kg
Chlorine	3.95E-05	kg
Chloroacetic acid	1.71E-08	kg
Chloroform	3.91E-08	kg
Chlorothalonil	1.02E-07	kg
Chlorpropham	5.60E-08	kg
Chlorpyrifos	1.21E-07	kg
Chromium	3.61E-08	kg
Cobalt	1.26E-08	kg
Cobalt-58	4.88E-08	Bq
Cobalt-60	9.26E-07	Bq
Copper	3.74E-08	kg
Cumene	5.36E-08	kg
Cyanamide	8.90E-08	kg
Cyclohexane	3.56E-08	kg
Cypermethrin	1.44E-08	kg
Decane	1.90E-08	kg
Diquat dibromide	2.39E-07	kg
Ethane	1.53E-06	kg
Ethane, 1,2-dichloro-	1.34E-08	kg
Ethanol	2.90E-08	kg
Ethene	1.16E-07	kg
Ethofumesate	9.47E-08	kg
Ethoprop	4.35E-08	kg
Ethyne	1.17E-08	kg
Fluoride	1.52E-08	kg
Folpet	1.03E-08	kg
Formaldehyde	3.26E-06	kg
Formic acid	4.69E-05	kg
Glyphosate	2.96E-06	kg
Heptane	1.58E-08	kg
Hexane	4.34E-07	kg
Hydrocarbons, chlorinated	1.12E-08	kg
Hydrocarbons, unspecified	1.20E-05	kg

TABLE 46. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF POLYETHER POLYOL FOR RIGID POLYURETHANE (CONTINUED)

	1 kg	
Atmospheric Emissions		
Hydrogen	1.34E-06	kg
Hydrogen-3, Tritium	2.79E-01	Bq
Hydrogen chloride	7.90E-05	kg
Hydrogen cyanide	2.80E-07	kg
Hydrogen fluoride	9.83E-06	kg
Hydrogen sulfide	1.83E-05	kg
Imidacloprid	1.10E-08	kg
Indoxacarb	1.48E-08	kg
Iodine-129	7.68E-05	Bq
Iodine-131	1.69E-03	Bq
Iodine-133	7.97E-08	Bq
Iodine-135	8.30E-08	Bq
Iron	1.09E-08	kg
Isobutane	7.26E-04	kg
Isoproturon	1.08E-07	kg
Kerosene	2.15E-07	kg
Ketones, unspecified	1.13E-08	kg
Krypton-85	7.55E+02	Bq
Krypton-87	2.66E-04	Bq
Krypton-88	2.65E-04	Bq
Krypton-89	6.97E-05	Bq
Lambda-cyhalothrin	2.30E-08	kg
Lead	3.75E-08	kg
Lead-210	9.39E-04	Bq
Linuron	7.77E-08	kg
Magnesium	7.23E-07	kg
Mancozeb	3.70E-07	kg
Maneb	1.10E-08	kg
Manganese	3.97E-08	kg
Metamitron	4.07E-07	kg
Metazachlor	7.37E-08	kg
Methane	9.58E-03	kg
Methane, biogenic	4.09E-03	kg
Methane, chlorodifluoro-, HCFC-22	5.35E-08	kg
Methane, dichloro-, HCC-30	3.47E-08	kg
Methanol	4.18E-07	kg
Methiocarb	3.40E-08	kg
Methomyl	1.15E-08	kg

TABLE 46. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF POLYETHER POLYOL FOR RIGID POLYURETHANE (CONTINUED)

	1 kg	
Atmospheric Emissions		
Metolachlor, (S)	1.07E-06	kg
Metribuzin	8.47E-08	kg
Monoethanolamine	5.71E-08	kg
Naphthalene	3.43E-08	kg
Napropamide	6.03E-08	kg
Nickel	1.13E-07	kg
Nitric oxide	3.13E-05	kg
Nitrobenzene	1.44E-08	kg
Nitrogen dioxide	1.56E-05	kg
Nitrogen monoxide	1.14E-05	kg
Nitrogen oxides	6.40E-03	kg
Nitrogen, atmospheric	8.75E-06	kg
Nitrous oxide	3.99E-04	kg
Organic substances, unspecified	4.26E-07	kg
Oxamyl	2.28E-08	kg
Oxygen	4.98E-06	kg
Ozone	1.62E-08	kg
Particulates, < 10 um	2.68E-04	kg
Particulates, < 2.5 um	1.50E-04	kg
Particulates, > 10 um	3.84E-05	kg
Particulates, > 2.5 um, and < 10um	4.70E-05	kg
Particulates, unspecified	3.79E-04	kg
Pendimethalin	3.81E-07	kg
Pentane	2.83E-07	kg
Pentane, 2,2,4-trimethyl-	4.35E-08	kg
Phenol	4.08E-08	kg
Pirimicarb	6.51E-08	kg
Polonium-210	1.16E-03	Bq
Potassium-40	6.42E-05	Bq
Propamocarb	4.39E-08	kg
Propanal	1.90E-08	kg
Propane	1.38E-06	kg
Propargite	1.08E-08	kg
Propene	2.79E-07	kg
Propylene	1.36E-04	kg
Propylene oxide	5.23E-04	kg
Prosulfocarb	5.02E-07	kg
Protactinium-234	4.50E-06	Bq

TABLE 46. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF POLYETHER POLYOL FOR RIGID POLYURETHANE (CONTINUED)

	1 kg	
Atmospheric Emissions		
Pyriproxyfen	1.16E-08	kg
Radioactive species, unspecified	3.69E+03	Bq
Radium-226	2.31E-02	Bq
Radium-228	1.18E-04	Bq
Radon-220	1.79E-03	Bq
Radon-222	2.60E+01	Bq
Selenium	8.64E-08	kg
Silicon	2.65E-08	kg
Sodium	1.47E-08	kg
Sodium hydroxide	5.99E-08	kg
Sulfate	1.86E-06	kg
Sulfur dioxide	2.21E-03	kg
Sulfur monoxide	3.09E-07	kg
Sulfur oxides	6.96E-04	kg
Sulfur trioxide	3.99E-07	kg
Sulfuric acid	3.10E-07	kg
Tebuconazole	1.51E-08	kg
Terbuthylazin	9.62E-08	kg
Thorium-228	1.77E-05	Bq
Thorium-230	1.13E-03	Bq
Thorium-232	3.04E-05	Bq
Thorium-234	4.50E-06	Bq
TOC, Total Organic Carbon	2.10E-06	kg
Toluene	2.40E-06	kg
Uranium-234	1.21E-03	Bq
Uranium-235	1.87E-04	Bq
Uranium-238	1.46E-03	Bq
Uranium alpha	2.45E-04	Bq
Vanadium	4.94E-08	kg
VOC, volatile organic compounds	3.69E-03	kg
Xenon-131m	2.38E-03	Bq
Xenon-133	1.51E-01	Bq
Xenon-135	7.25E-02	Bq
Xenon-137	2.24E-03	Bq
Xenon-138	5.03E-03	Bq
Xylene	7.82E-07	kg

TABLE 46. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF POLYETHER POLYOL FOR RIGID POLYURETHANE (CONTINUED)

	1 kg	
Waterborne Releases		
2-Methyl-1-propanol	1.06E-08	kg
2-Propanol	1.38E-08	kg
Acetaldehyde	1.59E-07	kg
Acetic acid	2.34E-03	kg
Acidity, unspecified	5.95E-08	kg
Acids, unspecified	1.74E-03	kg
Aclonifen	2.79E-08	kg
Actinides, radioactive, unspecified	5.35E-05	Bq
Aluminium	3.57E-06	kg
Americium-241	2.02E-05	Bq
Ammonia	8.45E-07	kg
Ammonium, ion	3.71E-06	kg
Aniline	2.17E-08	kg
Antimony-122	1.96E-08	Bq
Antimony-124	9.74E-06	Bq
Antimony-125	8.99E-06	Bq
AOX, Adsorbable Organic Halogen as Cl	3.27E-08	kg
Arsenic	1.28E-08	kg
Atrazine	2.22E-08	kg
Barium	1.81E-04	kg
Barium-140	8.57E-08	Bq
Benzene	6.85E-06	kg
Benzene, 1,2-dichloro-	5.10E-08	kg
Benzene, chloro-	7.45E-07	kg
Benzene, ethyl-	5.97E-07	kg
Bicarbonate, ion	1.28E-03	kg
Biphenyl	5.95E-07	kg
BOD5, Biological Oxygen Demand	5.44E-04	kg
Borate	4.46E-07	kg
Boron	9.35E-07	kg
Bromate	4.00E-08	kg
Bromide	2.77E-05	kg
Bromine	2.93E-08	kg
Butadiene	5.95E-07	kg
Butene	1.19E-08	kg
Calcium	2.66E-04	kg
Carbon-14	1.65E-03	Bq
Carbonate	4.54E-06	kg
Carboxylic acids, unspecified	1.70E-07	kg
Cerium-141	3.42E-08	Bq
Cerium-144	1.04E-08	Bq

TABLE 46. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF POLYETHER POLYOL FOR RIGID POLYURETHANE (CONTINUED)

	1 kg	
Waterborne Releases		
Cesium-134	1.04E-03	Bq
Cesium-137	1.58E-02	Bq
Chloramine	7.58E-08	kg
Chlorate	3.07E-07	kg
Chloridazon	1.59E-08	kg
Chloride	4.05E-03	kg
Chlorine	2.24E-08	kg
Chloroacetic acid	4.60E-07	kg
Chlorothalonil	1.13E-08	kg
Chlorpyrifos	1.35E-08	kg
Chromium	2.68E-07	kg
Chromium-51	1.02E-05	Bq
Cobalt-57	1.93E-07	Bq
Cobalt-58	8.50E-05	Bq
Cobalt-60	4.48E-03	Bq
COD, Chemical Oxygen Demand	4.43E-03	kg
Copper	1.47E-07	kg
Cumene	9.52E-08	kg
Curium alpha	2.68E-05	Bq
Cyanide	1.59E-08	kg
Decane	4.73E-08	kg
Diethylamine	1.03E-08	kg
Dimethyl phthalate	5.95E-08	kg
Dimethylamine	4.84E-08	kg
Diquat dibromide	2.66E-08	kg
Dissolved solids	1.29E-02	kg
DOC, Dissolved Organic Carbon	4.27E-06	kg
Ethane, 1,2-dichloro-	3.15E-08	kg
Ethanol	3.75E-07	kg
Ethene	5.97E-06	kg
Ethofumesate	1.05E-08	kg
Ethylamine	1.24E-08	kg
Ethylene glycol	5.98E-07	kg
Fluoride	3.87E-06	kg
Formaldehyde	7.18E-08	kg
Formic acid	2.04E-03	kg
Glyphosate	3.28E-07	kg
Hydrocarbons, unspecified	2.51E-03	kg
Hydrogen-3, Tritium	4.49E+01	Bq

TABLE 46. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF POLYETHER POLYOL FOR RIGID POLYURETHANE (CONTINUED)

	1 kg	
Waterborne Releases		
Iodide	3.11E-06	kg
Iodine-129	2.92E-03	Bq
Iodine-131	1.12E-04	Bq
Iodine-133	5.38E-08	Bq
Iron	8.83E-06	kg
Iron-59	1.48E-08	Bq
Isoprene	5.96E-08	kg
Isoproturon	1.20E-08	kg
Lanthanum-140	9.12E-08	Bq
Lead	2.18E-08	kg
Lead-210	3.00E-01	Bq
Lithium	1.37E-07	kg
Magnesium	5.30E-05	kg
Mancozeb	4.11E-08	kg
Manganese	1.13E-05	kg
Manganese-54	6.88E-04	Bq
Metamitron	4.52E-08	kg
Methane, dichloro-, HCC-30	1.06E-08	kg
Methanol	2.26E-07	kg
Metolachlor, (S)	1.19E-07	kg
Molybdenum-99	3.15E-08	Bq
Niobium-95	6.82E-07	Bq
Nitrate	4.02E-03	kg
Nitrate compounds	1.53E-06	kg
Nitrobenzene	5.75E-08	kg
Nitrogen	8.20E-06	kg
Oils, unspecified	3.15E-06	kg
Particulates, > 10 um	1.50E-05	kg
Pendimethalin	4.23E-08	kg
Petroleum oil	1.44E-08	kg
Phenol	1.44E-03	kg
Phenols, unspecified	1.44E-03	kg
Phosphate	7.77E-05	kg
Phosphorus	2.51E-05	kg
Plutonium	7.61E-05	Bq
Plutonium-alpha	4.35E-06	Bq
Polonium-210	4.58E-01	Bq

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TABLE 46. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF POLYETHER POLYOL FOR RIGID POLYURETHANE (CONTINUED)

	1 kg	
Waterborne Releases		
Potassium	1.36E-04	kg
Potassium-40	3.63E-02	Bq
Propene	9.64E-08	kg
Propionic acid	1.65E-08	kg
Propylene glycol	5.95E-07	kg
Prosulfocarb	5.57E-08	kg
Protactinium-234	8.65E-05	Bq
Radioactive species, alpha emitters	4.15E-04	Bq
Radioactive species, Nuclides, unspecified	1.40E+01	Bq
Radium-224	1.98E-03	Bq
Radium-226	7.41E-01	Bq
Radium-228	3.96E-03	Bq
Ruthenium-106	3.64E-04	Bq
Selenium	3.40E-08	kg
Silicate	3.99E-07	kg
Silicon	1.29E-07	kg
Silver-110	5.47E-05	Bq
Sodium	2.06E-03	kg
Sodium-24	2.38E-07	Bq
Sodium hydroxide	1.59E-03	kg
Strontium	8.50E-08	kg
Strontium-89	9.83E-07	Bq
Strontium-90	4.71E-02	Bq
Styrene	5.95E-06	kg
Sulfate	1.36E-03	kg
Sulfide	2.05E-06	kg
Sulfur	2.97E-05	kg
Sulfuric acid	4.73E-07	kg
Suspended solids, unspecified	5.21E-05	kg

TABLE 46. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF POLYETHER POLYOL FOR RIGID POLYURETHANE (CONTINUED)

	1 kg	
Waterborne Releases		
Technetium-99m	7.28E-07	Bq
Tellurium-123m	9.50E-07	Bq
Terbuthylazin	1.07E-08	kg
Thorium-228	1.16E-02	Bq
Thorium-230	1.17E-02	Bq
Thorium-232	1.80E-05	Bq
Thorium-234	8.65E-05	Bq
TOC, Total Organic Carbon	8.94E-05	kg
Toluene	6.02E-06	kg
Toluene, 2-chloro-	1.15E-08	kg
Uranium-234	1.12E-04	Bq
Uranium-235	1.65E-04	Bq
Uranium-238	1.60E-01	Bq
Uranium alpha	4.78E-03	Bq
VOC, volatile organic compounds, unspecified origin	1.44E-08	kg
Xylene	6.03E-07	kg
Zinc	5.32E-07	kg
Zinc-65	3.23E-06	Bq
Zirconium-95	3.74E-08	Bq

TABLE 47. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF PULTRUDED PRODUCTS

	1kg	
Environmental Emissions		
Atmospheric Emissions		
1-Butanol	3.5E-08	kg
1,4-Dioxane	2.2E-08	kg
4-Methyl-2-pentanone	3.4E-08	kg
Acetaldehyde	3.7E-07	kg
Acetic acid	1.9E-07	kg
Acetone	1.0E-05	kg
Acrolein	2.7E-07	kg
Actinides, radioactive, unspecified	2.8E-06	Bq
Aerosols, radioactive, unspecified	1.1E-07	Bq
Aldehydes, unspecified	4.4E-07	kg
Aluminium	8.8E-08	kg
Ammonia	8.9E-06	kg
Ammonium chloride	7.6E-07	kg
Argon-41	6.1E-04	Bq
Arsenic	5.0E-08	kg
Benzene	2.9E-05	kg
Benzene, 1,2,4-trimethyl-	3.5E-08	kg
Benzene, ethyl-	3.2E-05	kg
Boric acid	2.0E-07	kg
Bromine	9.9E-08	kg
Butadiene	6.7E-08	kg
Butane	1.1E-06	kg
Cadmium	1.7E-08	kg
Carbon-14	8.0E-04	Bq
Carbon dioxide	2.5E+00	kg
Carbon dioxide, biogenic	1.2E-06	kg
Carbon disulfide	2.0E-08	kg
Carbon monoxide	1.7E-03	kg
Carbon monoxide, biogenic	5.2E-05	kg
Carbonyl sulfide	5.2E-08	kg
Cesium-134	6.7E-08	Bq
Cesium-137	1.4E-07	Bq
Chlorine	5.0E-06	kg
Chromium	4.4E-08	kg
Cobalt	2.0E-08	kg
Cobalt-60	1.2E-08	Bq

TABLE 47. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF PULTRUDED PRODUCTS (CONTINUED)

	1kg	
Atmospheric Emissions		
Cumene	2.9E-05	kg
Cyanamide	1.2E-07	kg
Cyanide	1.4E-08	kg
Cyclohexane	4.7E-08	kg
Dicyclopentadiene	6.7E-07	kg
Dimethyl ether	2.6E-07	kg
Ethane	2.7E-08	kg
Ethene	1.3E-07	kg
Ethylene glycol	1.4E-06	kg
Ethylene oxide	2.2E-08	kg
Fluoride	2.6E-07	kg
Formaldehyde	3.6E-06	kg
Formic acid	1.4E-06	kg
Glyphosate	3.6E-08	kg
Hexane	5.0E-07	kg
Hydrocarbons, unspecified	1.2E-05	kg
Hydrogen	2.1E-07	kg
Hydrogen-3, Tritium	3.8E-03	Bq
Hydrogen chloride	1.3E-04	kg
Hydrogen cyanide	3.7E-07	kg
Hydrogen fluoride	5.1E-05	kg
Hydrogen peroxide	5.7E-08	kg
Hydrogen sulfide	4.0E-07	kg
Iodine-129	9.8E-07	Bq
Iodine-131	2.2E-05	Bq
Isobutane	2.2E-05	kg
Isobutyraldehyde	2.9E-07	kg
Kerosene	3.6E-07	kg
Krypton-85	9.1E+00	Bq
Krypton-85m	4.6E-05	Bq
Krypton-87	7.9E-06	Bq
Krypton-88	9.4E-06	Bq
Krypton-89	3.4E-06	Bq
Lead	7.3E-08	kg
Lead-210	2.3E-05	Bq
Magnesium	1.2E-06	kg
Maleic anhydride	1.6E-06	kg
Manganese	6.4E-08	kg

TABLE 47. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF PULTRUDED PRODUCTS (CONTINUED)

	1kg	
Atmospheric Emissions		
Mercaptans, unspecified	1.2E-06	kg
Mercury	1.9E-08	kg
Methane	6.2E-03	kg
Methane, biogenic	4.9E-05	kg
Methane, bromo-, Halon 1001	1.1E-08	kg
Methane, dichloro-, HCC-30	4.7E-08	kg
Methanol	6.3E-05	kg
Methyl acetate	9.4E-07	kg
Methyl methacrylate	5.2E-06	kg
Metolachlor, (S)	1.3E-08	kg
Naphthalene	4.0E-08	kg
Naphthalene, 1,2,3,4-tetrahydro-	2.2E-08	kg
Nickel	1.7E-07	kg
Niobium-95	7.6E-06	Bq
Nitric oxide	3.8E-07	kg
Nitrogen dioxide	5.5E-07	kg
Nitrogen monoxide	1.4E-07	kg
Nitrogen oxides	6.2E-03	kg
Nitrogen, atmospheric	1.2E-03	kg
Nitrous oxide	7.2E-05	kg
Oxygen	4.0E-04	kg
Particulates	1.8E-07	kg
Particulates, < 10 um	4.8E-04	kg
Particulates, < 2.5 um	1.5E-04	kg
Particulates, > 10 um	6.1E-05	kg
Particulates, > 2.5 um, and < 10um	1.0E-04	kg
Particulates, unspecified	4.8E-03	kg
Pentane, 2,2,4-trimethyl-	5.5E-08	kg
Phenol	3.3E-05	kg
Phthalic acid,branched and linear di c7-c11 alk*	2.2E-06	kg
Phthalic anhydride	8.3E-08	kg
Polonium-210	3.4E-05	Bq
Potassium-40	4.6E-06	Bq
Propane	7.8E-08	kg
Propene	1.3E-05	kg
Propylene	4.1E-06	kg
Propylene oxide	3.8E-05	kg
Protactinium-234	2.5E-07	Bq
Radioactive species, unspecified	6.1E+03	Bq

TABLE 47. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF PULTRUDED PRODUCTS (CONTINUED)

	1kg	
Atmospheric Emissions		
Radium-226	2.8E-04	Bq
Radium-228	4.3E-06	Bq
Radon-220	1.0E-04	Bq
Radon-222	3.7E-01	Bq
Selenium	1.5E-07	kg
Styrene	2.0E-03	kg
Sulfate	2.4E-08	kg
Sulfur dioxide	3.6E-03	kg
Sulfur oxides	1.1E-03	kg
Sulfur trioxide	5.8E-07	kg
Sulfuric acid	2.1E-06	kg
Thorium-228	8.8E-07	Bq
Thorium-230	1.4E-05	Bq
Thorium-232	1.4E-06	Bq
Thorium-234	2.5E-07	Bq
TOC, Total Organic Carbon	5.2E-06	kg
Toluene	3.0E-06	kg
Uranium-234	1.5E-05	Bq
Uranium-235	2.3E-06	Bq
Uranium-238	2.1E-05	Bq
Uranium alpha	4.0E-06	Bq
VOC, volatile organic compounds	2.6E-03	kg
Xenon-131m	5.4E-05	Bq
Xenon-133	3.7E-03	Bq
Xenon-133m	3.0E-06	Bq
Xenon-135	1.4E-03	Bq
Xenon-135m	3.4E-04	Bq
Xenon-137	3.4E-05	Bq
Xenon-138	1.1E-04	Bq
Xylene	4.3E-05	kg
Waterborne Releases		
1-Butanol	3.7E-08	kg
1,4-Dioxane	4.8E-08	kg
Acetaldehyde	8.7E-08	kg
Acetic acid	7.3E-05	kg
Acetone	5.0E-05	kg
Acidity, unspecified	7.5E-08	kg
Acids, unspecified	5.3E-05	kg
Actinides, radioactive, unspecified	7.3E-07	Bq
Aluminium	6.0E-06	kg
Americium-241	2.4E-07	Bq

TABLE 47. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF PULTRUDED PRODUCTS (CONTINUED)

	1kg	
Waterborne Releases		
Ammonia	4.6E-07	kg
Ammonium, ion	4.7E-06	kg
Aniline	1.0E-06	kg
Antimony-124	7.1E-06	Bq
Antimony-125	2.3E-07	Bq
AOX, Adsorbable Organic Halogen as Cl	2.2E-06	kg
Barium	8.9E-05	kg
Benzene	5.9E-05	kg
Benzene, ethyl-	2.0E-07	kg
Bicarbonate, ion	6.3E-04	kg
Biphenyl	1.1E-07	kg
BOD5, Biological Oxygen Demand	2.9E-03	kg
Boron	4.6E-07	kg
Bromide	1.3E-06	kg
Butadiene	1.1E-07	kg
Butyl acetate	4.8E-08	kg
Calcium	7.1E-05	kg
Carbon-14	2.1E-05	Bq
Carbonate	6.9E-08	kg
Cesium-134	1.3E-05	Bq
Cesium-137	2.0E-04	Bq
Chloride	5.5E-03	kg
Chromium-51	4.1E-07	Bq
Cobalt-57	2.6E-08	Bq
Cobalt-58	4.1E-06	Bq
Cobalt-60	5.6E-05	Bq
COD, Chemical Oxygen Demand	3.0E-03	kg
Copper	1.5E-07	kg
Cumene	7.8E-05	kg
Curium alpha	3.2E-07	Bq
Dimethyl phthalate	1.1E-08	kg
Dissolved solids	6.3E-03	kg
DOC, Dissolved Organic Carbon	5.8E-04	kg
Ethane, 1,2-dichloro-	2.2E-08	kg
Ethanol	9.0E-08	kg
Ethene	1.1E-06	kg
Ethylene glycol	2.2E-05	kg
Ethylene oxide	2.2E-07	kg

TABLE 47. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF PULTRUDED PRODUCTS (CONTINUED)

	1kg	
Waterborne Releases		
Fluoride	2.7E-06	kg
Formic acid	6.2E-05	kg
Hydrocarbons, unspecified	8.2E-05	kg
Hydrogen-3, Tritium	6.0E-01	Bq
Iodide	3.7E-08	kg
Iodine-129	3.5E-05	Bq
Iodine-131	2.7E-06	Bq
Iron	1.2E-05	kg
Iron-59	6.2E-06	Bq
Isoprene	1.2E-08	kg
Lead	2.9E-08	kg
Lead-210	3.6E-03	Bq
Magnesium	1.3E-05	kg
Manganese	7.8E-06	kg
Manganese-54	8.3E-06	Bq
Metallic ions, unspecified	2.1E-08	kg
Methanol	1.8E-07	kg
Niobium-95	1.8E-08	Bq
Nitrate	5.0E-05	kg
Nitrate compounds	1.2E-05	kg
Nitrobenzene	1.0E-06	kg
Nitrogen	5.5E-06	kg
Oils, unspecified	4.3E-06	kg
Organic substances, unspecified	1.2E-08	kg
Particulates, > 10 um	1.8E-07	kg
Phenol	2.1E-04	kg
Phosphate	1.6E-06	kg
Phosphorus	3.5E-07	kg
Plutonium	9.1E-07	Bq
Plutonium-alpha	5.2E-08	Bq
Polonium-210	5.5E-03	Bq
Potassium	6.5E-06	kg
Potassium-40	4.4E-04	Bq
Propene	3.1E-05	kg
Propylene glycol	1.1E-07	kg
Propylene oxide	5.4E-05	kg
Protactinium-234	1.5E-06	Bq
Radioactive species, Nuclides, unspecified	2.4E+01	Bq

TABLE 47. CRADLE-TO-GATE LCI RESULTS-ATMOSPHERIC EMISSIONS AND WATERBORNE RELEASES FOR 1 KILOGRAM OF PULTRUDED PRODUCTS (CONTINUED)

	1kg	
Waterborne Releases		
Radium-224	2.6E-05	Bq
Radium-226	9.1E-03	Bq
Radium-228	5.6E-05	Bq
Ruthenium-106	4.4E-06	Bq
Selenium	5.7E-08	kg
Silicate	1.9E-07	kg
Silicon	3.2E-08	kg
Silver-110	1.7E-06	Bq
Sodium	3.3E-03	kg
Sodium-24	3.0E-08	Bq
Sodium chloride	1.3E-03	kg
Sodium hydroxide	4.8E-05	kg
Strontium-89	4.1E-08	Bq
Strontium-90	6.1E-04	Bq
Styrene	1.2E-06	kg
Sulfate	7.0E-04	kg
Sulfide	1.2E-07	kg
Sulfur	3.6E-07	kg
Sulfuric acid	8.6E-07	kg
Suspended solids, unspecified	3.9E-04	kg
Technetium-99m	4.5E-08	Bq
Tellurium-123m	1.7E-08	Bq
Thorium-228	1.5E-04	Bq
Thorium-230	1.8E-04	Bq
Thorium-232	5.4E-07	Bq
Thorium-234	1.5E-06	Bq
TOC, Total Organic Carbon	6.3E-04	kg
Toluene	1.1E-06	kg
Uranium-234	1.9E-06	Bq
Uranium-235	2.6E-06	Bq
Uranium-238	1.9E-03	Bq
Uranium alpha	7.5E-05	Bq
Xylene	1.2E-07	kg
Zinc	2.7E-07	kg
Zinc-65	6.7E-07	Bq
Zirconium-95	3.1E-06	Bq

APPENDIX B. DATA SOURCES FOR UPSTREAM PROCESSES

This appendix includes a data source tables for upstream materials/processes associated with each input material and composite manufacturing process examined in this study. Each table in this appendix lists the data source(s) for all input materials necessary to develop the cradle-to-gate unit processes, as well as detailed comments regarding data development for each upstream input material. The unit process data sources for the final material or process are each discussed in the corresponding chapter within this report.

Average datasets for primary data were compiled using a combination of sources including ACMA data providers, research, and material data sheets. For data that were not available through public or private sources, LCI data were estimated using literature, stoichiometry, and average requirements for organic chemicals production per the Franklin Associates Private LCI Database.

The following data sources tables are included in this appendix:

- Table 48. Data Sources for Vinyl Ester Resin
- Table 49. Data Sources for Pultrusion

Data sources for the production of MDI and polyether polyol can be found in the attached Appendix of the ACC reports focused on those materials.

TABLE 48. DATA SOURCES FOR VINYL ESTER RESIN

Input Material	Data Sources	Comments
Epoxy Resin	Ecoinvent Database	Adapted from ecoinvent to reflect use of energy and material inputs for the U.S. context.
Maleic Anhydride	Ecoinvent Database	Adapted from ecoinvent to reflect use of energy and material inputs for the U.S. context.
Acrylic Acid	Ecoinvent Database	Adapted from ecoinvent to reflect use of energy and material inputs for the U.S. context.
Styrene	Virgin resin data compiled for the American Chemistry Council (ACC) by Franklin Associates and publicly available through the U.S. LCI Database.	Styrene data were updated in 2021 as shown in the ACC report, Cradle-to-Gate Life Cycle Analysis of General Purpose Polystyrene (GPPS) Resin.
BPA	Ecoinvent Database	Adapted from ecoinvent to reflect use of energy and material inputs for the U.S. context.
Silicon Dioxide (Silica)	U.S. LCI Database from Franklin Associates	Glass sand mining process data with silica inputs from nature added.

TABLE 49. DATA SOURCES FOR PULTRUSION

Input Material	Data Sources	Comments
Clay	Franklin Associates Private LCI Database	Reviewed and adapted the average of four primary datasets from the 1990s.
E-Glass	ACMA	Averaged datasets compiled for the ACMA project in 2012.
Epoxy Resin	Ecoinvent Database	Adapted from ecoinvent to reflect use of energy and material inputs for the U.S. context.
Styrene	Chemical data compiled for the American Chemistry Council (ACC) by Franklin Associates and publicly available through the U.S. LCI Database	Styrene data were updated in 2021 as shown in the ACC report, Cradle-to-Gate Life Cycle Analysis of General Purpose Polystyrene (GPPS) Resin.
Polyether Polyol	Chemical data compiled for the American Chemistry Council (ACC) by Franklin Associates and publicly available through the U.S. LCI Database	Polyether Polyol data were updated in 2022 as shown in the ACC report, Cradle-to-Gate Life Cycle Analysis of Polyether Polyol for Rigid Polyurethanes.
Methylene Diphenyl Diisocyanate (MDI)	Chemical data compiled for the American Chemistry Council (ACC) by Franklin Associates and publicly available through the U.S. LCI Database	MDI data were updated in 2022 as shown in the ACC report, Cradle-to-Gate Life Cycle Analysis of Methylene Diphenyl Diisocyanate (MDI).
Vinyl Ester Resin	ACMA	Averaged datasets compiled for the current ACMA project.
UPR	ACMA	Averaged datasets compiled for the ACMA project in 2012.
Pultrusion Process	ACMA	Averaged datasets compiled for the current ACMA project.