
CRADLE-TO-GATE LIFE CYCLE ANALYSIS OF POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANES

Final Report

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PREFACE

This life cycle assessment of Polyether Polyol for Flexible Foam resin was commissioned and funded by the American Chemistry Council (ACC) Plastics Division to update the original data in the 2011 report, **Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors**, as well as the U.S. LCI plastics database. The report was made possible through the cooperation of ACC member and non-member companies, who provided data for the production of olefins, chlorine/sodium hydroxide, ethylene oxide, and polyether polyol for flexible foam polyurethanes.

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

Franklin Associates gratefully acknowledges the significant contribution to this project by Allison Chertack, Prapti Muhuri, Mike Levy (First Environment Inc., formerly ACC), and Keith Christman of ACC in leading this project. Also acknowledged are the following companies: BASF Corporation, Covestro LLC, Dow Chemical Company, and Huntsman Corporation who graciously provided primary Life Cycle Inventory data for polyether polyol production for flexible foam polyurethanes. Their effort in collecting data has added considerably to the quality of this LCA report.

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

December, 2022

TABLE OF CONTENTS

INTRODUCTION	1
STUDY GOAL AND SCOPE	3
STUDY GOAL AND INTENDED USE	3
FUNCTIONAL UNIT	3
SCOPE AND BOUNDARIES	3
<i>Technological Scope</i>	5
<i>Temporal and Geographic Scope</i>	5
<i>Exclusions from the Scope</i>	6
INVENTORY AND IMPACT ASSESSMENT RESULTS CATEGORIES	6
DATA SOURCES	9
DATA QUALITY ASSESSMENT	10
DATA ACCURACY AND UNCERTAINTY	12
METHOD	12
<i>Raw Materials Use for Internal Energy in Steam Crackers</i>	12
<i>Coproduct Allocation</i>	13
<i>Electricity Grid Fuel Profile</i>	14
<i>Electricity/Heat Cogeneration</i>	15
LIFE CYCLE INVENTORY AND IMPACT ASSESSMENT RESULTS	18
ENERGY DEMAND	18
<i>Cumulative Energy Demand</i>	18
<i>Energy Demand by Fuel Type</i>	21
SOLID WASTE	22
WATER CONSUMPTION	24
GLOBAL WARMING POTENTIAL	26
ACIDIFICATION POTENTIAL	28
EUTROPHICATION POTENTIAL	30
OZONE DEPLETION POTENTIAL	31
PHOTOCHEMICAL SMOG FORMATION	32
COMPARISON OF 2022 AND 2011 LCI AND LCIA POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANE RESULTS	34
ENERGY COMPARISON	35
SOLID WASTE COMPARISON	37
GLOBAL WARMING POTENTIAL COMPARISON	38
APPENDIX: POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANES MANUFACTURE	39
OIL PALM FRESH FRUIT CULTIVATION AND HARVESTING	40
CRUDE PALM OIL PROCESSING	41
METHANOL PRODUCTION	43
GLYCERINE PRODUCTION	45
PROPYLENE OXIDE PRODUCTION	45
ETHYLENE OXIDE PRODUCTION	48
POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANES PRODUCTION	58
REFERENCES	61

LIST OF ACRONYMS

(Alphabetical)

ACC	AMERICAN CHEMISTRY COUNCIL
AP	ACIDIFICATION POTENTIAL
BOD	BIOCHEMICAL OXYGEN DEMAND
COD	CHEMICAL OXYGEN DEMAND
CFC	CHLOROFLUOROCARBON
DOE	DEPARTMENT OF ENERGY
EGRID	EMISSIONS & GENERATION RESOURCE INTEGRATED DATABASE
EIA	ENERGY INFORMATION ADMINISTRATION
EP	EUTROPHICATION POTENTIAL
ERG	EASTERN RESEARCH GROUP, INC
EQ	EQUIVALENTS
GHG	GREENHOUSE GAS
GJ	GIGAJoule
GREET	GREENHOUSE GASES, REGULATED EMISSIONS, AND ENERGY USE IN TECHNOLOGIES
GWP	GLOBAL WARMING POTENTIAL
HCFC	HYDROCHLOROFLUOROCARBON
IPCC	INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
ISO	INTERNATIONAL ORGANIZATION FOR STANDARDIZATION
LCA	LIFE CYCLE ASSESSMENT
LCI	LIFE CYCLE INVENTORY
LCIA	LIFE CYCLE IMPACT ASSESSMENT
LPG	LIQUEFIED PETROLEUM GAS
MJ	MEGAJoule
MM	MILLION
MTBE	METHYL TERTIARY BUTYL ETHER
NAPAP	NATIONAL ACID PRECIPITATION ASSESSMENT PROGRAM
NM VOC	NON-METHANE VOLATILE ORGANIC COMPOUNDS

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

CRADLE-TO-GATE LIFE CYCLE ASSESSMENT OF POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANES

INTRODUCTION

This study provides the American Chemistry Council (ACC), their members, users of the U.S. LCI Database, and the public at large with information about the life cycle inventory and impacts for the production of polyether polyol for flexible foam polyurethanes, which is a long chain polyether polyol. Flexible foam polyurethanes are used in a variety of end use applications including cushions for furniture and automobiles, mattress pads and carpet pads. Life cycle assessment (LCA) is recognized as a scientific method for making comprehensive, quantified evaluations of the environmental benefits and tradeoffs commonly for the entire life cycle of a product system, beginning with raw material extraction and continuing through disposition at the end of its useful life as shown in Figure 1 below. This cradle-to-gate LCA includes the life cycle stages shown in the dashed box including the “Raw Materials Acquisition” and “Materials Manufacture” boxes in the figure.

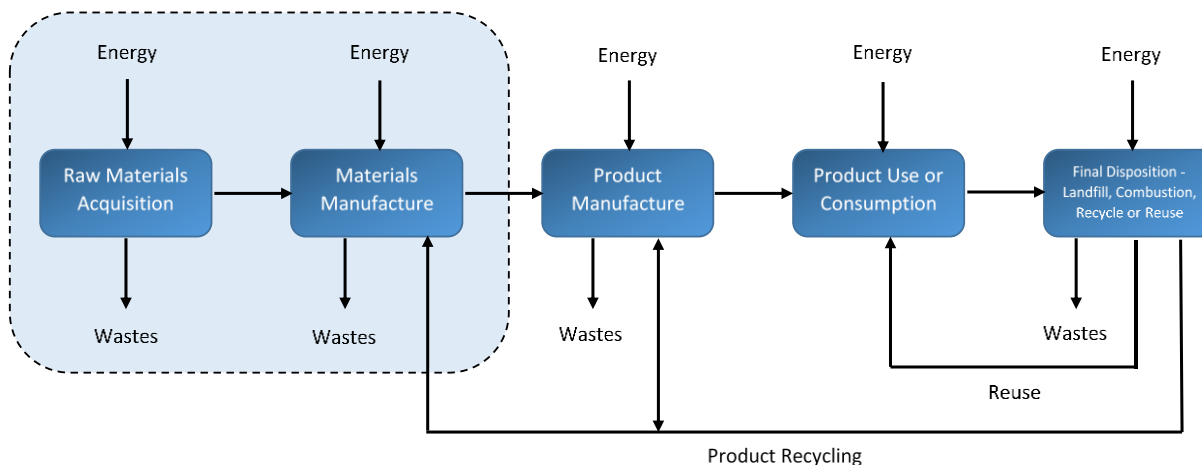


Figure 1. General materials flow for “cradle-to-grave” analysis of a product system. The dashed box indicates the boundaries of this analysis.

The results of this analysis are useful for understanding production-related impacts and are provided in a manner suitable for incorporation into full life cycle assessment studies. The information from an LCA can be used as the basis for further study of the potential improvement of resource use and environmental impacts associated with product systems. It can also pinpoint areas (e.g., material components or processes) where changes would be most beneficial in terms of reducing energy use or potential impacts.

A life cycle assessment commonly examines the sequence of steps in the life cycle of a product system, beginning with raw material extraction and continuing through material

production, product fabrication, use, reuse, or recycling where applicable, and final disposition. This cradle-to-gate life cycle inventory (LCI) and life cycle impact assessment (LCIA) quantifies the total energy requirements, energy sources, water consumption, atmospheric pollutants, waterborne pollutants, and solid waste resulting from the production of the long-chain polyether polyol. It is considered a cradle-to-gate boundary system because this analysis ends with the polyether polyol production. The system boundaries stop at the polyether polyol production so that the data can be linked to a fabrication process, where it is an input material, and end-of-life data to create full life cycle inventories for a variety of applications, such as flexible molded foams for bedding, seating and furniture or in the chemical industry to produce adhesives, sealants, elastomers or coatings. The method used for this inventory has been conducted following internationally accepted standards for LCI and LCA methodology as outlined in the International Organization for Standardization (ISO) 14040:2006 and 14044:2006 standard documents¹.

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

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

The LCI identifies and quantifies the material inputs, energy consumption, water consumption, and environmental emissions (atmospheric emissions, waterborne wastes, and solid wastes) over the defined scope of the study. The LCI unit process data for fresh fruit bunch harvesting, palm kernel production and processing, methanol, glycerine, propylene oxide, ethylene oxide, and polyether polyol unit is shown separately in the attached Appendix. The LCI data for the olefins system is shown in the appendix of a separate report, *Cradle-to-Gate Life Cycle Analysis of Olefins*². The LCI data for the chlorine/sodium hydroxide system is shown in the appendix of a separate report, *Cradle-to-Gate Life Cycle Analysis of Polyvinyl Chloride*³. All publicly available unit processes will be made available to the Department of Energy (DOE) National Renewable Energy Laboratory (NREL) who maintains the U.S. LCI Database. The ethylene oxide unit process data is confidential and is not provided.

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

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

² Cradle-to-Gate Life Cycle Analysis of Olefins. Franklin Associates. Submitted to the Plastics Division of the American Chemistry Council. April, 2020.

³ 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.

STUDY GOAL AND SCOPE

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

STUDY GOAL AND INTENDED USE

The purpose of this LCA is to document the LCI data and then evaluate the environmental profile of polyether polyol, which is a long chain polyol, for flexible foam polyurethanes. The intended use of the study results is twofold:

- To provide the LCA community and other interested parties with average North American LCI data for polyether polyol for flexible foam polyurethanes; and
- To provide information about the environmental burdens associated with the production of polyether polyol for flexible foam polyurethanes. The LCA results for polyether polyol production can be used as a benchmark for evaluating future updated polyether polyol results for North America.

According to ISO 14040 and 14044 standards, a peer review of this Cradle-to-Gate Life Cycle Analysis of Polyether Polyol for Flexible Foam Polyurethanes report is not required as no comparative assertions of competing materials or products are made in this study.

This report is the property of ACC acting on behalf of its Plastics Division and may be used by the trade association or members of ACC's Plastics Division or the general public at ACC's discretion.

FUNCTIONAL UNIT

The function of polyether polyol is its required inclusion to make flexible foam polyurethane products, for example, in bedding or seating or within adhesives. As the study boundary concludes at the production of the polyether polyol, a mass functional unit has been chosen. Results for this analysis are shown on a basis of both 1,000 pounds and 1,000 kilograms of polyether polyol produced.

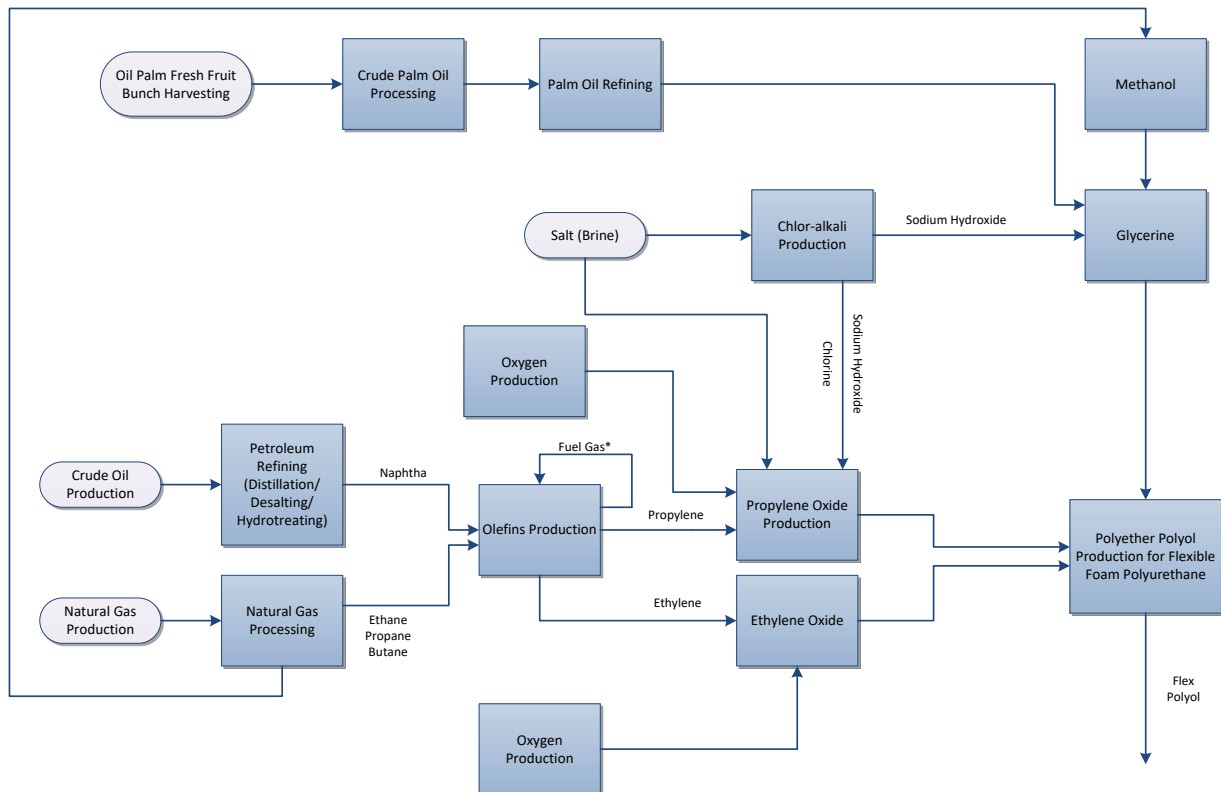
SCOPE AND BOUNDARIES

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

- Raw material extraction (e.g., extraction of petroleum and natural gas as feedstocks) through glycerine, propylene oxide and ethylene oxide, as well as incoming transportation for each process; and

- Polyether polyol for flexible foam polyurethanes manufacture, including incoming transportation for each input material.

Because upstream olefin and chlor-alkali manufacture impacts the results for the production of propylene oxide and ethylene oxide used to produce polyether polyol for flexible foam polyurethanes, discussion of chlorine, sodium hydroxide, propylene and ethylene data and meta-data is included throughout this report. However, the LCI data for the olefins system is provided in the appendix of the separate report, *Cradle-to-Gate Life Cycle Analysis of Olefins*, and the chlor-alkali system is provided in the appendix of the separate report, *Cradle-to-Gate Life Cycle Analysis of Polyvinyl Chloride*. This report presents LCI results, as well as LCIA results, for the production of polyether polyol. Figure 2 presents the flow diagram for the production of polyether polyol for flexible foam polyurethanes. A unit process description and tables for each box shown in the flow diagram can be found in the attached appendix or in the mentioned reports previously released. The fuel gas shown in Figure 2 is created from offgas produced in the olefins process. The composition of the fuel gas was considered for each individual olefin plant and an appropriate higher heating value was used to best represent the fuel gas composition. In the case when the fuel gas was a mixed composition, a weighted average of the higher heating values was used.



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

Figure 2. Flow diagram for the Production of Polyether Polyol for Flexible Foam Polyurethanes.

Technological Scope

The technology used to manufacture polyether polyol for flexible foam polyurethanes in North America begins with the introduction of a potassium hydroxide catalyst to a polyol initiator, such as a triol. This solution is reacted with propylene oxide and ethylene oxide to form an intermediate. Water is then added to this intermediate. A solvent is introduced, which absorbs the polyol from the water/catalyst. The density difference between the aqueous & organic phases is used to separate the two phases. Finally, the polyol is purified of solvent, side products and water through distillation.

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

Temporal and Geographic Scope

As part of the data quality assessment, time period and geography were considered. All data submitted for polyether polyol represent the years 2015 or 2017. For the polyether polyol primary data, companies were requested to provide data for the year 2015, which is the most recent full year of polyether polyol production prior to the project initiation date. Companies providing data were given the option to collect data from the year preceding or following 2015 if either year would reflect more typical production conditions. Three plants provided data for the year 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 from 2015 or 2017 was representative of an average year for polyether polyol production at their company.

The geographic scope of the analysis is the manufacture of polyether polyol in North America. Polyether polyol data were collected from plants all located in the United States. Some input materials were modeled using North American databases such as the U.S. LCI database and Franklin Associates' private database, as well as ecoinvent. Datasets from ecoinvent were adapted to U.S. conditions to the extent possible (e.g., by using U.S. average grid electricity to model production of process electricity reported in the European data sets). The U.S. electricity grid from 2016 was taken from information in Emissions & Generation Resource Integrated Database (eGRID) 2016 database.

Exclusions from the Scope

The following are not included in the study:

- **Miscellaneous materials and additives.** Selected materials such as catalysts, initiators, ancillary materials, or other additives which total less than one percent by weight of the net process inputs are typically not included in assessments. This follows the ISO cut-off criteria rules in ISO 14040 and 14044. It is possible that production of some substances used in small amounts may be energy and resource intensive or may release toxic emissions; however, the impacts would have to be very large in proportion to their mass in order to significantly affect overall results and conclusions. For this study, no use of resource-intensive or high-toxicity chemicals or additives was identified. Therefore, the results for the polyether polyol are not expected to be understated by any significant amount due to substances that may be used in small amounts.
- **Capital equipment, facilities, and infrastructure.** The energy and wastes associated with the manufacture of buildings, roads, pipelines, motor vehicles, industrial machinery, etc. are not included. The energy and emissions associated with production of capital equipment, facilities, and infrastructure generally become negligible when averaged over the total output of product or service provided over their useful lifetimes.
- **Space conditioning.** The fuels and power consumed to heat, cool, and light manufacturing establishments are omitted from the calculations when possible. For manufacturing plants that carry out thermal processing or otherwise consume large amounts of energy, space conditioning energy is quite low compared to process energy. The data collection forms developed for this project specifically requested that the data provider either exclude energy use for space conditioning or indicate if the reported energy requirements included space conditioning. Energy use for space conditioning, lighting, and other overhead activities is not expected to make a significant contribution to total energy use for the resin system.
- **Support personnel requirements.** The energy and wastes associated with research and development, sales, and administrative personnel or related activities have not been included in this study. Similar to space conditioning, energy requirements and related emissions are assumed to be quite small for support personnel activities.

INVENTORY AND IMPACT ASSESSMENT RESULTS CATEGORIES

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

reporting basis, using characterization factors that express the impact of each substance relative to a reference substance.

The LCI and LCIA results categories and methods applied in this study are displayed in Table 1. This study addresses global, regional, and local impact categories. For most of the impact categories examined, the TRACI 2.1 method, developed by the United States Environmental Protection Agency (EPA) specific to U.S. conditions and updated in 2012, is employed.⁴ For the category of Global Warming Potential (GWP), contributing elementary flows are characterized using factors reported by the Intergovernmental Panel on Climate Change (IPCC) in 2013 with a 100 year time horizon.⁵ In addition, the following LCI results are included in the results reported in the analysis:

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

⁴ Bare, J. C. [Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts \(TRACI\), Version 2.1 - User's Manual](#); EPA/600/R-12/554 2012.

⁵ IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Table 1. Summary of LCI/LCIA Impact Categories

	Impact/Inventory Category	Description	Unit	LCIA/LCI Methodology
LCI Categories	Total energy demand	Measures the total energy from point of extraction; results include both renewable and non-renewable energy sources.	Million (MM) Btu and megajoule (MJ)	Cumulative energy inventory
	Non-renewable energy demand	Measures the fossil and nuclear energy from point of extraction.	MM Btu and MJ	Cumulative energy inventory
	Renewable energy demand	Measures the hydropower, solar, wind, and other renewables, including landfill gas use.	MM Btu and MJ	Cumulative energy inventory
	Solid waste by weight	Measures quantity of fuel and process waste to a specific fate (e.g., landfill, waste-to-energy (WTE)) for final disposal on a mass basis	Lb and kg	Cumulative solid waste inventory
	Water consumption	Freshwater withdrawals which are evaporated, incorporated into products and waste, transferred to different watersheds, or disposed into the land or sea after usage	Gallons and Liters	Cumulative water consumption inventory
LCIA Categories	Global warming potential	Represents the heat trapping capacity of the greenhouse gases. Important emissions: CO ₂ fossil, CH ₄ , N ₂ O	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 ₂ S	Lb SO ₂ eq and kg SO ₂ eq	TRACI v2.1
	Eutrophication potential	Assesses impacts from excessive load of macro-nutrients to the environment. Important emissions: NH ₃ , NO _x , chemical oxygen demand (COD) and biochemical oxygen demand (BOD), N and P compounds	Lb N eq and kg N eq	TRACI v2.1
	Ozone depletion potential	Measures stratospheric ozone depletion. Important emissions: chlorofluorocarbon (CFC) compounds and halons	Lb CFC-11 eq and kg CFC-11 eq	TRACI v2.1
	Smog formation potential	Determines the formation of reactive substances (e.g. tropospheric ozone) that cause harm to human health and vegetation. Important emissions: NO _x , benzene, toluene, ethylbenzene, xylene (BTEX), non-methane volatile organic compound (NMVOC), CH ₄ , C ₂ H ₆ , C ₄ H ₁₀ , C ₃ H ₈ , C ₆ H ₁₄ , acetylene, Et-OH, formaldehyde	Lb kg O ₃ eq and kg O ₃ eq	TRACI v2.1

DATA SOURCES

The purpose of this study is to develop a life cycle profile for polyether polyol using the most recent data available for each process. A production-weighted average was calculated for the polyether polyol data (production for the year 2015 and 2017) collected for this analysis. The ethylene oxide data is a weighted average of four primary datasets collected from two producers for 2015. The propylene oxide data is an average of three different technologies from the 1990s. The technologies are all still in use in North America, and the weightings of each dataset have been updated to reflect recent use of these technologies. The olefins data was also calculated as a production-weighted average of primary datasets for 2015. Secondary data was researched in 2017 for crude oil extraction and refining and natural gas production and processing. Secondary sources were used for methanol, oxygen, palm kernel oil production and glycerine production. All included processes are shown in the appendix at the end of the report or within a previously released report.

LCI data for the production of polyether polyol were collected from four producers (four plants) in North America within the United States. All companies provided data for the years 2015 or 2017. A weighted average was calculated from the data collected and used to develop the LCA model. The captured polyether polyol production amount is approximately 90 percent of the polyether polyol production in North America in 2015⁶. This percentage was estimated using the amount of polyol used for flexible foam in the end use table in this document. No coproducts are produced within polyether polyol manufacture.

LCI data for the production of ethylene oxide were collected from two producers in North America within the United States for the year 2015. Due to having fewer than three ethylene oxide producers, this confidential data is unavailable for inclusion in the appendix as a unit process; however, a system process (cradle-to-ethylene oxide manufacture) inventory table has been included. A weighted average was calculated from these data collected and used to develop the LCA model.

LCI data for the production of olefins, including propylene used in the manufacture of propylene oxide and ethylene used to produce ethylene oxide, were collected from three producers (ten plants) in North America – all in the United States. All companies provided data for the year 2015. A weighted average was calculated from the data collected and used to develop the LCA model. Propylene and ethylene are coproducts during olefins production, and a mass basis was used to allocate the environmental burdens among these coproducts.

LCI data for the chlor-alkali process were collected from three producers (three plants) using the membrane technology in the United States. Two of the plants provided data for the year 2015, while one provided data for the year 2017. A weighted average was calculated from the data collected and used to develop the LCA model. A combination of stoichiometric and mass allocation was used for the chlorine, sodium hydroxide, and hydrogen coproducts from this process. Stoichiometric allocation was used for the material inputs, while mass allocation was used for all other inputs and outputs. This follows the same method used by

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

PlasticsEurope for their chlor-alkali process LCA. Small amounts of hydrogen were considered a coproduct at the plants. In some cases, much of the hydrogen created was used as a fuel in the chlor-alkali or down-stream PVC processes or it was used to make hydrochloric acid on-site.

DATA QUALITY ASSESSMENT

ISO 14044:2006 lists a number of data quality requirements that should be addressed for studies intended for use in public comparative assertions. The data quality goals for this analysis were to use data that are (1) geographically representative for the polyether polyol is based on the locations where material sourcing and production take place, and (2) representative of current industry practices in these regions. As described in the previous section, four companies each provided data from 2015-2017, which was geographically representative data for all primary polyether polyol data collected for this LCA.

The incoming material and fuel datasets for polyether polyol manufacture were either updated using geographical and technologically relevant data from government or privately available statistics/studies within the US or drawn from either The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model or ecoinvent⁷. Datasets from ecoinvent were adapted to U.S. conditions to the extent possible (e.g., by using U.S. average grid electricity to model production of process electricity reported in the European data sets). The data sets used were the most current and most geographically and technologically relevant data sets available during the data collection phase of the project.

Consistency, Completeness, Precision: Data evaluation procedures and criteria were applied consistently to all primary data provided by the participating producers for all data collected. All primary data obtained specifically for this study were considered the most representative available for the systems studied. Data sets were reviewed for completeness and material balances, and follow-up was conducted as needed to resolve any questions about the input and output flows, process technology, etc. The aggregated averaged datasets were also reviewed by the providing companies as compared to the provided dataset. Companies were requested to comment on their own data normalized to 1000 pounds as well as the industry average dataset normalized to 1000 pounds.

Representativeness: Polyether polyol manufactured in North America is commonly produced using catalyzed propoxylation and ethoxylation of multi-functional initiators within the United States. The four companies provided data from their facilities using technology ranging from average to state-of-the-art.

LCI data for the production of ethylene oxide were collected from two producers in North America within the United States for the year 2015. Companies providing data were given

⁷ Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment*, [online] 21(9), pp.1218–1230. Available at: <<http://link.springer.com/10.1007/s11367-016-1087-8>> [Accessed Sept, 2018].

the option to collect data from the year preceding or following 2015 if either year would reflect more typical production conditions. After reviewing individual company data in comparison to the average, each manufacturer verified data from 2015 was a representative year for ethylene oxide production in North America.

LCI data for the production of propylene oxide was taken from an older source for 3 types of technologies currently used; however, there are two newer technologies that make up approximately 10 percent of the production of propylene oxide in 2015. It is unknown how not including these technologies will affect the LCI data for this unit process. It is also unknown whether the LCI data for the older technologies have changed significantly. ACC is advised to collect data for the propylene oxide unit process in future updates.

The LCI data for the olefins system is shown in the appendix of a separate report, *Cradle-to-Gate Life Cycle Analysis of Olefins*⁸. Primary data were collected from olefin manufacturers from the year 2015. Companies providing data were given the option to collect data from the year preceding or following 2015 if either year would reflect more typical production conditions. After reviewing individual company data in comparison to the average, each manufacturer verified data from 2015 was a representative year for ethylene, butadiene and pygas production in North America.

LCI data from the sources of input materials specific to each company providing data was not available for this analysis. Average U.S. statistics were used for refined petroleum products and processed natural gas to develop the average olefins unit process data. As impacts from crude oil and natural gas may vary depending on transportation requirements some variability in data and impact on LCA results should be expected.

The average polyether polyol unit process data was based on the best available data at the time the study was conducted. As in all LCA studies, the ability to develop a representative average is determined by the number of companies willing to participate. Data from this analysis was used to develop the most representative average for polyether polyol production as was possible.

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

Order of Magnitude: In some cases, emissions data in primary data averages were reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only as an order

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

of magnitude. An order of magnitude of a number is the smallest power of 10 used to represent that number. For example, if the average of two data points for a particular emission is 2.5E-4, the amount would be shown as 1.0E-4 to ensure confidentiality of the data providers but allow the impact assessment tool to include a close estimate of the amount within any pertinent impact categories. When order of magnitude is used in the LCI data shown in the Appendix of this report, it is clearly noted by an asterisk next to the amount.

Uncertainty: Uncertainty issues and uncertainty thresholds applied in interpreting study results are described in the following section.

DATA ACCURACY AND UNCERTAINTY

In LCA studies with thousands of numeric data points used in the calculations, the accuracy of the data and how it affects conclusions is truly a complex subject, and one that does not lend itself to standard error analysis techniques. Techniques such as Monte Carlo analysis can be used to assess study uncertainty, but the greatest challenge is the lack of uncertainty data or probability distributions for key parameters, which are often only available as single point estimates. However, steps are taken to ensure the reliability of data and results, as previously described.

The accuracy of the environmental results depends on the accuracy of the numbers that are combined to arrive at that conclusion. For some processes, the data sets are based on actual plant data reported by plant personnel, while other data sets may be based on engineering estimates or secondary data sources. Primary data collected from actual facilities are considered the best available data for representing industry operations. In this study, primary data were used to model the polyether polyol, ethylene oxide, chlor-alkali products, and steam cracking of the olefins. All data received were carefully evaluated before compiling the production-weighted average data sets used to generate results. Supporting background data were drawn from credible, widely used databases including the US LCI database, GREET, and ecoinvent.

METHOD

The LCA has been conducted following internationally accepted standards for LCA as outlined in the ISO 14040 and 14044 standards, which provide guidance and requirements for conducting LCA studies. However, for some specific aspects of LCA, the ISO standards have some flexibility and allow for choices to be made. The following sections describe the approach to each issue used in this study. Many of these issues are specific to the olefins produced at the steam crackers.

Raw Materials Use for Internal Energy in Steam Crackers

Some of the raw material inputs to the steam cracker create gases that are combusted to provide energy for the steam cracker, decreasing the amount of purchased energy required for the reaction. Data providers listed this energy as fuel gas or off-gas and, in many cases,

supplied the heating value of this gas. Using this information, Franklin Associates calculated the amount of raw material combusted within the steam cracker to produce this utilized energy source.

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

Coproduct Allocation

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

Environmental burdens are allocated among the coproducts when raw materials and emissions cannot be directly attributed to one of several product outputs from a system. It has long been recognized that the practice of allocating the environmental burdens among the coproducts is less desirable than being able to identify which inputs lead to specific outputs. In this study, co-product allocations are necessary because of multiple useful outputs from the “upstream” chemical process involved in producing polyether polyol and olefins.

Franklin Associates follows the guidelines for allocating the environmental burdens among the coproducts as shown in the ISO 14044:2006 standard on life cycle assessment requirements and guidelines⁹. 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 14044:2006 section 4.3.4.2, when allocation cannot be avoided, the preferred partitioning approach should reflect the underlying physical relationships between the different products or functions.

Material Coproducts

Some processes lend themselves to physical allocation because they have physical parameters that provide a good representation of the environmental burdens of each coproduct. Examples of various allocation methods are mass, stoichiometric, elemental, reaction enthalpy, and economic allocation. Simple mass and enthalpy allocation have been

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

chosen as the common forms of allocation in this analysis. However, these allocation methods were not chosen as a default choice but made on a case-by-case basis after consideration of the chemistry and basis for production.

Material coproducts were created in all the intermediate chemical process steps collected for this analysis, but no coproducts were created in the primary polyether polyol production. The material coproducts from olefins production for all plants included propylene, pyrolysis gasoline, butadiene, ethane, hydrogen, acetylene, crude benzene, and small amounts of various heavy end products. The material coproduct for the chlor-alkali process includes chlorine, sodium hydroxide, and hydrogen. No material coproducts were created in the ethylene oxide production.

A portion of the inputs and outputs calculated for the coproducts were removed from the total inputs and outputs, so that the remaining inputs and outputs only represented the main product in each unit process. The ratio of the mass of the coproduct over the total mass output was removed from the total inputs and outputs of the process, and the remaining inputs and outputs are allocated over the material products (Equation 1).

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

where

IO = Input/Output Matrix to produce all products/coproducts

M_{CP} = Mass of Coproduct

M_{Total} = Mass of all Products and Coproducts

Energy Coproducts Exported from System Boundaries

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

Electricity Grid Fuel Profile

Electricity production and distribution systems in North America are interlinked. Users of electricity, in general, cannot specify the fuels used to produce their share of the electric power grid. Data for this analysis was collected from plants in the United States and Mexico. The U.S. average fuel consumption by electrical utilities was used for the electricity within this analysis. This electricity data set uses the Emissions & Generation Resource Integrated Database (eGRID) 2016 database¹⁰. The 2016 grid was used for consistency with the age of

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

the collected resin process data. Table 2 provides a breakdown of energy sources and the contribution by percentage of each source to the grid mix.

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

Electricity/Heat Cogeneration

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

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

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

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

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

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

1. **Fuels consumed and emissions generated by the boiler:** The majority of data providers for this study reported natural gas as the fuel used for cogeneration. According to 2016 industry statistics, natural gas accounted for 75 percent of industrial cogeneration, while coal and biomass accounted for the largest portion of the remaining fuels used¹¹.
2. **Kilowatt-Hours of Electricity Generated:** In this analysis, the data providers reported the kilowatt-hours of electricity from cogeneration. The Btu of fuel required for this electricity generation was calculated by multiplying the kilowatt-hours of electricity by 6,826 Btu/kWh (which utilizes a thermal to electrical conversion efficiency of 50 percent). This Btu value was then divided by the Btu value of fuel consumed in the cogeneration boiler to determine the electricity allocation factor.

The 50 percent conversion efficiency was an estimate after reviewing energy information administration (EIA) fuel consumption and electricity net generation data from cogeneration plants in 2016.¹² The straight average conversion efficiency for 2016 for electricity production in cogeneration plants within this database is a little more than 55 percent; however, the range of efficiency calculated per individual cogeneration plant was 23% to 87%. The 50 percent estimate of conversion efficiency was used previously in the 2011 database and so was estimated for continued use within this analysis, due to the variability of the individual cogeneration plants. Unit process data for cogeneration of electricity is provided by kWh, so that a change of efficiency could easily be applied during modeling.

3. **Thermal Output of Steam Exiting Electricity Generation:** In this analysis, the data providers stated the pounds and pressure of steam from cogeneration. The thermal output (in Btu) of this steam was calculated from enthalpy tables (in most cases steam ranged from 1,000 to 1,200 Btu/lb). An efficiency of 80 percent was used for the industrial boiler to calculate the amount of fuel used¹³. This Btu value was then divided by the Btu value of fuel

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

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

¹³ United States Environmental Protection Agency (EPA). *Methods for Calculating CHP Efficiency*. Accessed online at <https://www.epa.gov/chp/methods-calculating-chp-efficiency>.

consumed in the cogeneration boiler to determine the steam allocation factor. The 80 percent efficiency used is common for a conventional natural gas boiler, which should not change when considering the steam portion of the cogeneration system. Pounds of steam, temperature and pressure were provided by participating plants. Steam tables were used to calculate energy amounts, which was divided by the efficiency and converted to natural gas amounts in cubic feet.

LIFE CYCLE INVENTORY AND IMPACT ASSESSMENT RESULTS

This section presents baseline results for the following LCI and LCIA results for both 1,000 pounds and 1,000 kilograms of polyether polyol (long chain) used in flexible foam polyurethane:

Life cycle inventory results:

- Cumulative energy demand
- Non-renewable energy demand
- Renewable energy demand
- Total energy by fuel type
- Solid waste by weight
- Water consumption

Life cycle impact assessment results:

- Global warming potential
- Acidification potential
- Eutrophication potential
- Ozone depletion potential
- Smog formation potential

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

- Cradle-to-incoming materials – includes the raw materials through the production of propylene oxide, ethylene oxide, and glycerine.
- Polyether polyol for flexible foam polyurethanes production – is the gate-to-gate unit process and includes the production of fuels used in the process.

Tables and figures are provided for polyether 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 chemical/resin stated in the term (e.g., cradle-to-polyether polyol and polyether polyol system are interchangeable). The phrase “gate-to-gate” is defined as including only the onsite process/fuels.

ENERGY DEMAND

Cumulative Energy Demand

Cumulative energy demand results include all renewable and non-renewable energy sources used for process and transportation energy, as well as material feedstock energy. Process energy includes direct use of fuels, including the use of fossil fuels, hydropower, nuclear, wind, solar, and other energy sources to generate electricity used by processes. Fuel energy is the energy necessary to create and transport the fuels to the processes. The feedstock

energy is the energy content of the resources removed from nature and used as material feedstocks for the olefins production (e.g., the energy content of oil and gas used as material feedstocks), which are the main inputs to propylene oxide and ethylene oxide used to produce polyether polyol.

The average total energy required to produce the long chain polyether polyol is 37.7 million Btu per 1,000 pounds of polyether polyol or 87.8 gigajoule (GJ) per 1,000 kilograms of polyether polyol. Table 3 shows total energy demand for the life cycle of polyether polyol production. The polyether polyol production energy has been split out from the energy required for incoming materials, including the production of petroleum extraction and refining, natural gas production and processing, olefins (ethylene/propylene), oxygen, brine, chlorine, sodium hydroxide, ethylene oxide, propylene oxide, oil palm fresh fruit cultivation and harvesting, crude palm oil processing, palm oil refining, methanol, and glycerine. Only approximately 2 percent of the total energy is required to produce the polyether polyol itself. The remaining 98 percent is used to create the raw and intermediate materials. A little less than 90 percent of the required energy is used to create the propylene oxide (cradle-to-propylene oxide), which makes up 86 percent of the incoming material required to create polyether polyol.

Table 3. Total Energy Demand for Polyether Polyol for Flexible Foam Polyurethanes

Basis: 1,000 pounds			
	Total Energy	Non-Renewable Energy	Renewable Energy
	<i>MM Btu</i>	<i>MM Btu</i>	<i>MM Btu</i>
Cradle-to-Incoming Materials	37.0	36.7	0.32
Flex Polyol Production	0.74	0.73	0.01
Total	37.7	37.4	0.33
Basis: 1,000 kilograms			
	Total Energy	Non-Renewable Energy	Renewable Energy
	<i>GJ</i>	<i>GJ</i>	<i>GJ</i>
Cradle-to-Incoming Materials	86.1	85.3	0.74
Flex Polyol Production	1.71	1.70	0.02
Total	87.8	87.0	0.76
Percentage			
	Total Energy	Non-Renewable Energy	Renewable Energy
	<i>%</i>	<i>%</i>	<i>%</i>
Cradle-to-Incoming Materials	98.0%	97.2%	0.85%
Flex Polyol Production	2.0%	1.9%	0.02%
Total	100%	99.1%	0.9%

Non-renewable energy demand includes the use of fossil fuels (petroleum, natural gas, and coal) for process energy, transportation energy, and as material feedstocks (e.g., oil and gas used as feedstocks for the production of the olefins), as well as use of uranium to generate the share of nuclear energy in the average U.S. kWh. For the polyether polyol, 99.1 percent of the total energy comes from non-renewable sources. The renewable energy demand consists of landfill gas used for process energy in olefins production and electricity derived from renewable energy sources (primarily hydropower, as well as wind, solar, and other sources). The renewable energy (0.02 GJ/1000 kg) used at the polyether polyol plant comes solely from hydropower and other renewable sources (geothermal, solar, etc.) from electricity production.

The energy content of natural gas and petroleum used as raw material inputs for the production of ethylene and propylene used to produce incoming materials for the polyether polyol is included in the cradle-to-incoming material amounts in Table 3. The energy inherent in these raw materials is called material feedstock energy. Of the total energy (87.8 GJ) for 1,000 kg of polyether polyol, 38.5 GJ is material feedstock energy. Figure 3 provides the breakdown of the percentage of total energy required for material feedstock energy versus the process and fuel energy amounts needed to produce the polyether polyol. Approximately 44 percent of the total energy is inherent energy in the natural gas and petroleum used as a feedstock to create olefins, which in turn are used to create propylene oxide and ethylene oxide making polyether polyol. Of the feedstock sources for ethylene and propylene, between 86 and 90 percent comes from natural gas, while 10 to 14 percent of the feedstock sources come from oil. A majority of the feedstock split for olefins is natural gas.

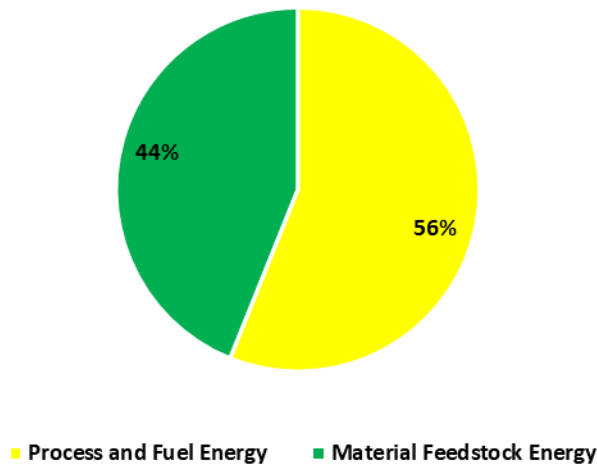


Figure 3. Process/Fuel and Material Feedstock Percentages for Polyether Polyol for Flexible Foam Polyurethanes

Energy Demand by Fuel Type

The total energy demand by fuel type for polyether polyol is shown in Table 4 and the percentage mix is shown in Figure 4. Natural gas and petroleum together make up over 90 percent of the total energy used. As shown in Figure 3, this is partially due to the material feedstock energy used to create the olefins, which are intermediate chemical inputs to polyether polyol. These material feedstock fuels are part of the energy shown in the natural gas and petroleum split out in the following table and figure. The gate-to-gate production energy for 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.

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, besides other non-renewables used for electricity.

Of the results for polyether polyol production shown in Table 4 and Figure 4, 83 percent of the energy used (73.3 GJ/87.8 GJ) is from natural gas. At the polyether polyol plant, 87 percent of the energy used (1.48 GJ/1.71 GJ) comes from natural gas. Of that natural gas used at the polyether polyol plant, 55 percent is combusted on-site, while 36 percent is required to create electricity through the grid. Petroleum comprises approximately 7 percent (6.3 GJ/87.8 GJ) of the fuel used for the polyether polyol production system. Almost 90 percent of the petroleum used for the polyether polyol plant is combusted during transport of materials to the plant. The coal use shown is almost fully from combustion for electricity use. Electricity use is high for the chlor-alkali process, the products of which are major inputs to some of the technologies producing propylene oxide. The 2016 U.S. electricity grid is used for this study. In this grid, approximately 30 percent of the electricity production in the U.S. uses coal as a fuel source, while a third of the grid comes from natural gas and 20 percent from uranium. The hydropower, nuclear, and other energy are all used to create electricity, with the exception of a small amount of landfill gas used in the olefins production shown within other renewables.

Table 4. Energy Demand by Fuel Type for Polyether Polyol for Flexible Foam Polyurethanes

Basis: 1,000 pounds							
Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable	
<i>MM Btu</i>	<i>MM Btu</i>	<i>MM Btu</i>	<i>MM Btu</i>	<i>MM Btu</i>	<i>MM Btu</i>	<i>MM Btu</i>	
Cradle-to-Incoming Materials	37.0	30.9	2.69	1.87	1.25	0.134	0.19
Flex Polyol Production	0.74	0.64	0.023	0.042	0.028	0.003	0.004
Total	37.7	31.5	2.71	1.91	1.28	0.14	0.19
Basis: 1,000 kilograms							
Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable	
<i>GJ</i>	<i>GJ</i>	<i>GJ</i>	<i>GJ</i>	<i>GJ</i>	<i>GJ</i>	<i>GJ</i>	
Cradle-to-Incoming Materials	86.1	71.8	6.25	4.35	2.91	0.31	0.44
Flex Polyol Production	1.71	1.48	0.05	0.10	0.065	0.0069	0.010
Total	87.8	73.3	6.31	4.45	2.97	0.32	0.45
Percentage of Total							
Total Energy	Natural Gas	Petroleum	Coal	Nuclear	Hydropower	Other Renewable	
%	%	%	%	%	%	%	
Cradle-to-Incoming Materials	98.0%	81.8%	7.1%	5.0%	3.3%	0.4%	0.5%
Flex Polyol Production	2.0%	1.7%	0.1%	0.1%	0.1%	0.0%	0.0%
Total	100%	83.5%	7.2%	5.1%	3.4%	0.4%	0.5%

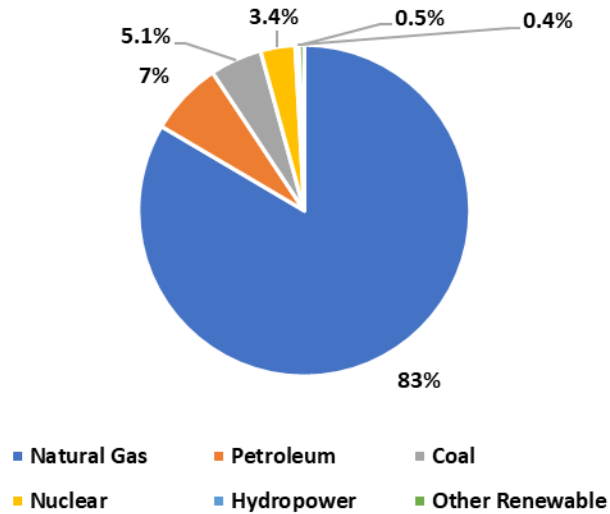


Figure 4. Percentage of Energy Separated by Fuel Type for Polyether Polyol for Flexible Foam Polyurethanes

SOLID WASTE

Solid waste results include the following types of wastes:

- **Process wastes** that are generated by the various processes from raw material acquisition through production of the resin (e.g., sludges and residues from chemical reactions and material processing steps)

- **Fuel-related wastes** from the production and combustion of fuels used for process energy and transportation energy (e.g., refinery wastes, coal combustion ash)

No postconsumer wastes of the polyether polyol are included in this analysis as the boundaries end with resin production and do not include production, use, or disposal of products made from the resin.

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

Results for solid waste by weight for the polyether polyol system are shown in Table 5 and Figure 5. The solid wastes have been separated into hazardous and non-hazardous waste categories, as well as by the cradle-to-incoming materials and the polyether polyol plant. As shown in Figure 5, only 5 percent of the total solid waste is associated with the polyether polyol unit process. Of that amount at the plant, almost 60 percent is process solid waste, while 30 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.

The majority of solid waste, 95 percent, comes from the production of incoming materials used to produce polyether polyol. Focusing on direct input systems, the propylene oxide system (cradle-to-propylene oxide) creates more than 90 percent of the incoming solid wastes. Looking at specific unit processes, the coal extraction and combustion for the production of electricity accounts for almost 60 percent of the solid waste from incoming materials. Natural gas and crude oil extraction with refining/processing are used to create the main input materials used in polyether polyol. The solid wastes created from the extraction and processing of these raw materials create a little more than 30 percent of the solid wastes from the cradle-to-incoming materials. The olefins plant process wastes make up 4 percent of the solid wastes of the incoming materials.

Solid wastes are shown separated by hazardous and non-hazardous wastes in Table 5. This separation was done only where primary data was collected, or if a secondary data source was clear that the solid waste was of a hazardous nature. The process solid wastes from oil and natural gas were classified as non-hazardous due to exclusions found in resource conservation and recovery act (RCRA) hazardous wastes regulations or other EPA hazardous wastes regulations. No solid wastes were stated as hazardous in the data sources for oil and gas. Only 1.2 percent of the total solid wastes were considered hazardous wastes. Of that percentage, 68 percent comes from the olefins plant and most of the remaining amount coming from the polyether polyol plant.

Table 5 also provides a breakout of the total solid wastes by the disposal fate. Of the total hazardous waste, approximately two-thirds are incinerated without energy capture, and most of the remaining one-third is sent to waste-to-energy. Focusing specifically on the non-

hazardous solid waste produced, 95 percent of the non-hazardous solid waste is landfilled, while most of the remainder is incinerated without energy capture.

Table 5. Total Solid Wastes for Polyether Polyol for Flexible Foam Polyurethanes

Basis: 1,000 pounds									
Total Solid Waste	Hazardous Wastes				Non-Hazardous Wastes				
	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total	
<i>lb</i>	<i>lb</i>	<i>lb</i>	<i>lb</i>	<i>lb</i>	<i>lb</i>	<i>lb</i>	<i>lb</i>	<i>lb</i>	<i>lb</i>
Cradle-to-Incoming Materials	121	0	1.02	0.003	1.02	0.0004	4.54	115	120
Flex Polyol Production	5.98	0.48	0.00	0.00	0.48	0.00	0.00	5.50	5.50
Total	127	0.48	1.02	0.003	1.50	0.0004	4.54	121	125
Basis: 1,000 kilograms									
Total Solid Waste	Hazardous Wastes				Non-Hazardous Wastes				
	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total	
<i>kg</i>	<i>kg</i>	<i>kg</i>	<i>kg</i>	<i>kg</i>	<i>kg</i>	<i>kg</i>	<i>kg</i>	<i>kg</i>	<i>kg</i>
Cradle-to-Incoming Materials	121	0	1.02	0.003	1.02	0.0004	4.54	115	120
Flex Polyol Production	5.98	0.48	0.00	0.00	0.48	0.00	0.00	5.50	5.50
Total	127	0.48	1.02	0.003	1.50	0.0004	4.54	121	125
Percentage of Total									
Total Solid Waste	Hazardous Wastes				Non-Hazardous Wastes				
	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total	
%	%	%	%	%	%	%	%	%	%
Cradle-to-Incoming Materials	95%	0%	0.8%	0.0%	0.8%	0.0%	3.6%	91%	94%
Flex Polyol Production	5%	0.4%	0.0%	0.0%	0.4%	0.0%	0.0%	4%	4%
Total	100%	0.4%	0.8%	0.0%	1.2%	0.0%	3.6%	95%	99%

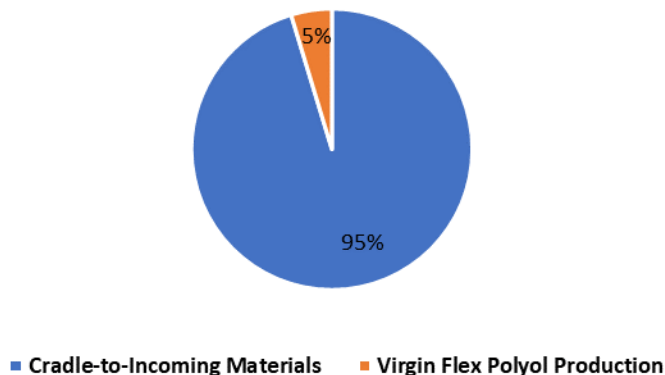


Figure 5. Percentage of Total Solid Wastes for Polyether Polyol for Flexible Foam Polyurethanes System

WATER CONSUMPTION

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

water consumption includes evaporative losses associated with thermal generation of electricity from fossil and nuclear fuels, as well as evaporative losses due to establishment of dams for hydropower.

Water consumption results for polyether polyol production are shown in Table 6 and Figure 6. The greatest portion of consumption of water within the polyether polyol comes from the cradle-to-incoming materials (92 percent). When looking at the individual unit processes, the brine required for chlor-alkali and one of the propylene oxide technologies consumes the most water at a little less than 40 percent of the total. Another large contributor for water consumption is the electricity used during all processes due to evaporative losses in the use of hydropower, which makes up approximately 25 percent of the total water consumption. The primary water consumption data for olefins, which consumes 13 percent of the total, 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 natural gas extraction and processing and crude oil refining total to a little more than 7 percent of the total water consumption, as does the chlor-alkali process creating chlorine and sodium hydroxide. 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 7 percent of the total, while the remaining 1 percent is consumed during the creation of hydropower.

Table 6. Water Consumption for Polyether Polyol for Flexible Foam Polyurethanes

	Total Water Consumption		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	<i>Gallons</i>	<i>Liters</i>	<i>%</i>
Cradle-to-Incoming Materials	2,177	18,164	92%
Flex Polyol Production	183	1,529	8%
Total	2,360	19,692	100%

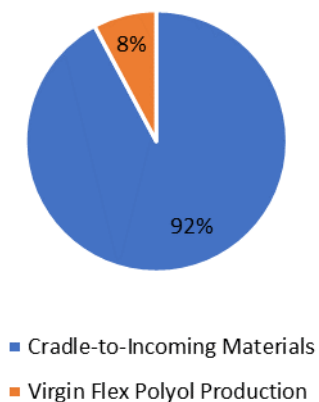


Figure 6. Water Consumption for Polyether Polyol for Flexible Foam Polyurethanes

GLOBAL WARMING POTENTIAL

The primary atmospheric emissions reported in this analysis that contribute over 99 percent of the total global warming potential for each system are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. Other contributors include some hydrochlorofluorocarbons (HCFCs) and chlorofluorocarbons (CFCs), but these contribute less than 0.1 percent of the total shown. Greenhouse gas emissions are mainly from combustion. In the primary data collected for olefins, ethylene oxide, and polyether polyol, combustion emissions from flare have been included as process emissions and so their totals may be overstated by small amounts due to the inclusion of combustion of fuel used during the flare. Data providers were asked to estimate percentages of greenhouse gases from flares or emission control processes apart from that of the combustion of fuels.

The 100-year global warming potential (GWP) factors for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2013¹⁴ are: fossil carbon dioxide 1, fossil methane 28, and nitrous oxide 265. The GWP factor for a substance represents the relative global warming contribution of a pound of that substance compared to a pound of carbon dioxide. The weights of each greenhouse gas are multiplied by its GWP factor to arrive at the total GWP results. Although normally GWP results are closely related to the energy results, the feedstock energy is not associated with GWP because feedstock energy is embodied in the resin material, not energy from combustion of the fuel.

In Table 7 and Figure 7, the life cycle GWP results for the Polyether polyol system are displayed. Of the total, 96 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, ethylene oxide, and glycerine) with the remaining associated with the production of the polyether polyol. Approximately 90 percent of this total for the incoming materials is associated with the cradle-to-propylene oxide material, which accounts for 86 percent of the inputs by weight.

For the polyether polyol production, only 4 percent of the total GWP from greenhouse gases are released from the polyol unit process. The process greenhouse gases released on-site at the polyether polyol plants are 17 percent of the total polyol production GWP; this is due to the thermal oxidizer, which is considered a mix of process and fuel-based emissions. The remaining GWP from the polyether polyol plants comes from either natural gas combustion (43 percent of the polyether polyol amount) or electricity (35 percent of the polyether polyol amount). While the remaining 5 percent of the polyether polyol GWP comes from fuel combustion for incoming transport of materials.

¹⁴ IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Table 7. Global Warming Potential for Polyether Polyol for Flexible Foam Polyurethanes

	Global Warming Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	<i>lb CO2 eq</i>	<i>kg CO2 eq</i>	%
Cradle-to-Incoming Materials	3,084	3,084	96%
Flex Polyol Production	121	121	4%
Total	3,205	3,205	100%

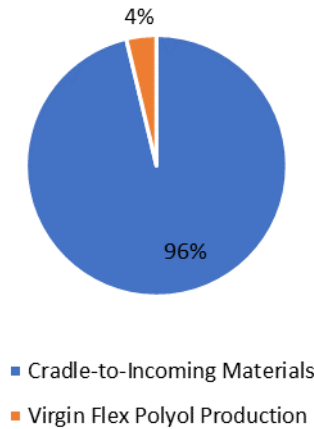


Figure 7. Global Warming Potential for Polyether Polyol for Flexible Foam Polyurethanes

Figure 8 displays the cradle-to-gate polyether polyol GWP separated by process contribution. This figure illustrates the percentages of GWP specific to process emissions at individual unit processes (e.g., olefins production), as well as to fuel-related emissions from the combustion of fuels and fuel combustion for transportation. Only processes creating at least one percent of the total GWP have been shown individually; all processes contributing less than one percent have been grouped into “all other processes.”

The largest amount of the GWP is created by the combustion of natural gas, coal, and oil in both industrial and utility boilers, which accounts for 58 percent of the total GWP. The steam cracking of olefins produces a little more than 16 percent of the GWP, which comes directly from the release of greenhouse gases at the plants, much of this from emission control processes. The natural gas extraction, processing and transport by pipeline used as a material input to the olefins plant comprises 15 percent of the total GWP. One to two percent of the total comes from oil extraction and refining, palm oil production, and transport of the materials (except natural gas). All other processes are less than 1 percent for any individual process and comprises 6 percent of the total GWP. The “all other processes” category includes the process greenhouse gases released at the polyether polyol plants, which account

for only 0.6 percent of the total; this is due to flaring or emission control processes, which is considered a mix of process and fuel-based emissions.

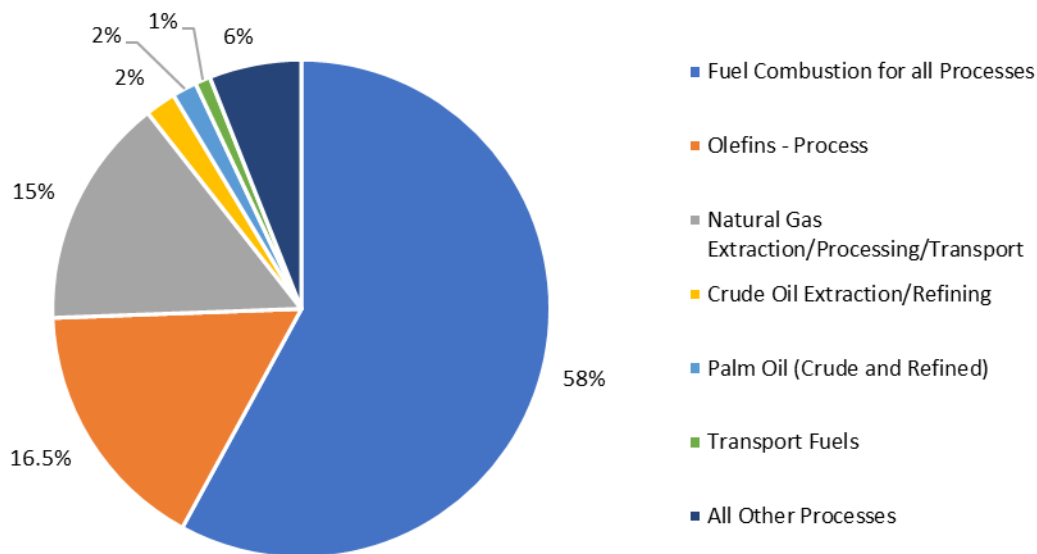


Figure 8. Global Warming Potential by Process Contribution

ACIDIFICATION POTENTIAL

Acidification assesses the potential of emissions to contribute to the formation and deposit of acid rain on soil and water, which can cause serious harm to plant and animal life as well as damage to infrastructure. Acidification potential modeling in TRACI incorporates the results of an atmospheric chemistry and transport model, developed by the U.S. National Acid Precipitation Assessment Program (NAPAP), to estimate total North American terrestrial deposition due to atmospheric emissions of NO_x and SO_2 , as a function of the emissions location.^{15,16}

Acidification potential (AP) impacts are typically dominated by fossil fuel combustion emissions or emissions from the extraction and processing of natural gas and oil, particularly sulfur dioxide (SO_2) and nitrogen oxides (NO_x). The combustion emissions of all fuels make up almost half of the total AP throughout the cradle-to-gate production of polyether polyols with emissions from the combustion of coal to generate grid electricity being the largest

¹⁵ Bare JC, Norris GA, Pennington DW, McKone T. (2003). TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, *Journal of Industrial Ecology*, 6(3-4): 49-78. Available at URL: http://mitpress.mit.edu/journals/pdf/jiec_6_3_49_0.pdf.

¹⁶ 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>.

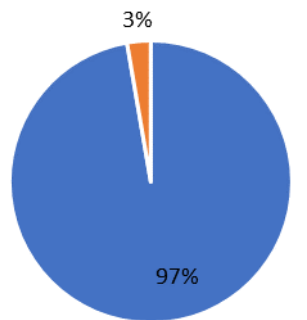
single contributor (40 percent). Natural gas extraction and processing emissions comprise another 40 percent of the total AP.

Table 8 shows total acidification potential results for the polyether polyol system. Results are shown graphically in Figure 9. In the AP category, only 3 percent of the AP is coming from polyether polyol production, while the remaining 97 percent comes from the raw and intermediate material unit processes. Process emissions from the polyether polyol plant produce 0.1 percent of the total AP. Of the rest of the 3 percent for the polyether polyol production, about fifty percent comes from electricity (combustion of coal and natural gas), 30 percent from the combustion of natural gas onsite, and 20 percent is produced by incoming transport.

Of the remaining 97 percent of the AP category created by incoming materials, 90 percent of the total AP is created during the production of propylene oxide, which makes up 86 percent of the inputs by mass.

Table 8. Acidification Potential for Polyether Polyol for Flexible Foam Polyurethanes

	Acidification Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	<i>lb SO2 eq</i>	<i>kg SO2 eq</i>	%
Cradle-to-Incoming Materials	8.85	8.85	97%
Flex Polyol Production	0.25	0.25	3%
Total	9.11	9.11	100%



- Cradle-to-Incoming Materials
- Virgin Flex Polyol Production

Figure 9. Acidification Potential for Polyether Polyol for Flexible Foam Polyurethanes

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.¹⁷ The TRACI characterization factors for eutrophication are the product of a nutrient factor and a transport factor.¹⁸ The nutrient factor is based on the amount of plant growth caused by each pollutant, while the transport factor accounts for the probability that the pollutant will reach a body of water. Atmospheric emissions of nitrogen oxides (NO_x) as well as waterborne emissions of nitrogen, phosphorus, ammonia, biochemical oxygen demand (BOD), and chemical oxygen demand (COD) are the main contributors to eutrophication impacts.

The greatest portion of the EP amount, 40 percent, is attributed to the extraction and processing of natural gas for the materials and fuels used throughout the cradle-to-gate polyether polyol system. Eutrophication potential (EP) results for polyether polyol are shown in Table 9 and illustrated in Figure 10. The production of the raw and intermediate materials used to create polyether polyol contributes 97 percent of the EP results. The emissions coming from the cradle-to-gate propylene oxide system comprise 63 percent of the EP impact results. It should be noted that 29 percent of the EP impact total comes from the cradle-to-gate glycerine system, which includes growing palm kernels used to produce palm oil, which then is used to manufacture glycerine. On a mass percentage, glycerine is approximately 3 percent of the total input to polyether polyol.

Table 9. Eutrophication Potential for Polyether Polyol for Flexible Foam Polyurethanes

	Eutrophication Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	<i>lb N eq</i>	<i>kg N eq</i>	%
Cradle-to-Incoming Materials	0.51	0.51	97%
Flex Polyol Production	0.017	0.017	3%
Total	0.53	0.53	100%

¹⁷ 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.

¹⁸ Bare JC, Norris GA, Pennington DW, McKone T. (2003). TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, *Journal of Industrial Ecology*, 6(3-4): 49-78. Available at URL: http://mitpress.mit.edu/journals/pdf/jiec_6_3_49_0.pdf.

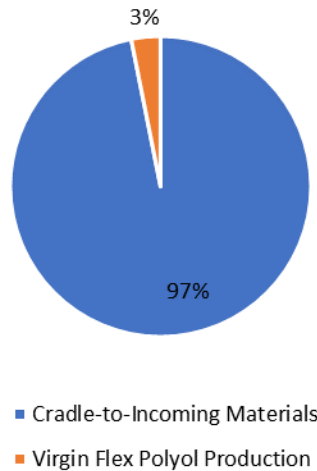


Figure 10. Eutrophication Potential for Polyether Polyol for Flexible Foam Polyurethanes

The gate-to-gate polyether polyol production generates 3 percent of the EP impact as seen in Table 9, with over a third of that amount released at the plant site. However, the main emissions contributing were provided by less than 3 plants and so are shown as an order of magnitude. These emissions include BOD and COD waterborne emissions, which are expected to be released from all plants. 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).

OZONE DEPLETION POTENTIAL

Stratospheric ozone depletion potential (ODP) is the reduction of the protective ozone within the stratosphere caused by emissions of ozone-depleting substance (e.g., CFCs and halons). The ozone depletion impact category characterizes the potential to destroy ozone based on a chemical’s reactivity and lifetime. Effects related to ozone depletion can include skin cancer, cataracts, material damage, immune system suppression, crop damage, and other plant and animal effects. For the polyether polyol system, the main sources of emissions contributing to ODP are minute amounts of a few CFCs, HCFCs, and halons emitted. Some are emitted during the extraction and refining of petroleum, which is used as fuel and material in the production of olefins, and some are associated with refrigerants leaks.

The greatest portion of the ODP amount, 42 percent, is attributed to the extraction and refining of oil for the materials and fuels used throughout the cradle-to-gate polyether polyol system. Table 10 shows total ODP results for the polyether polyol system, which are also shown graphically in Figure 11. The ODP amount shown in the cradle-to-incoming materials, 85 percent of the total ODP, include emissions from crude oil extraction and refining. Much of the remaining ODP for those incoming materials are attributed to the production of

pesticides used during cultivation and harvesting of the palm kernel oil used to produce the glycerine.

Ozone depletion results for the polyether polyol unit process are dominated by a small amount of refrigerant reported by less than 3 plants, which caused an order of magnitude to be used. This means there is a probability that this amount may be overstated or understated in the average. Discussions with the plants revealed that refrigerant leaks do happen occasionally but are not common on a regular annual basis.

Table 10. Ozone Depletion Potential for Polyether Polyol for Flexible Foam Polyurethanes

	Ozone Depletion Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	<i>lb CFC-11 eq</i>	<i>kg CFC-11 eq</i>	%
Cradle-to-Incoming Materials	2.9E-06	2.9E-06	85%
Flex Polyol Production	5.1E-07	5.1E-07	15%
Total	3.4E-06	3.4E-06	100%

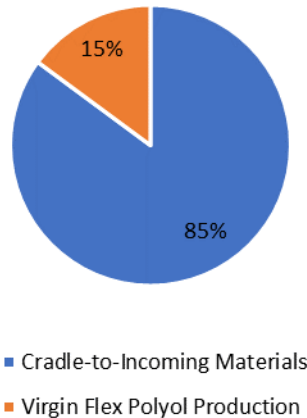


Figure 11. Ozone Depletion Potential for Polyether Polyol for Flexible Foam Polyurethanes

PHOTOCHEMICAL SMOG FORMATION

The photochemical ozone creation potential (POCP) impact category, also referred to as smog formation potential, characterizes the potential of airborne emissions to cause photochemical smog. The creation of photochemical smog occurs when sunlight reacts with NO_x and volatile organic compounds (VOCs), resulting in tropospheric (ground-level) ozone

and particulate matter. Endpoint effects of such smog creation can include increased human mortality, asthma, and deleterious effects on plant growth.¹⁹ Smog formation impact are generally dominated by emissions associated with fuel combustion, so that impacts are higher for life cycle stages and components that have higher process fuel and transportation fuel requirements. For cradle-to-resin production of polyether polyol, NO_x makes up 90 percent of the smog formation emissions, with VOCs consisting of almost 9 percent.

Smog formation potential results for polyether polyol are displayed in Table 11 and illustrated in Figure 12. Approximately 97% of the POCP impact results are associated with production of the raw and intermediate materials. The olefins and propylene oxide plants release 10 percent of the total emissions resulting the POCP. Fifty-five percent of the total POCP impact results are from the natural gas and oil extraction. The combustion of fuels in boilers, equipment, and for transport release emissions that create 30 percent of the POCP total amount.

The remaining 3 percent of the POCP impact is from polyether polyol production. An estimated 0.2 percent of the total emissions resulting in the POCP impact results are released at the polyether polyol plant as process emissions. The remaining percentage in the polyether polyol production is almost equally from combustion of fuels onsite, from emissions from generation of electricity used in the plant, and from the fuels used to transport incoming materials.

Table 11. Photochemical Smog Formation Potential for Polyether Polyol for Flexible Foam Polyurethanes

	Photochemical Smog Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	<i>lb O3 eq</i>	<i>kg O3 eq</i>	%
Cradle-to-Incoming Materials	199	199	97%
Flex Polyol Production	6.1	6.1	3%
Total	205	205	100%

¹⁹ Bare, J. C. [Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts \(TRACI\), Version 2.1 - User's Manual](#); EPA/600/R-12/554 2012.

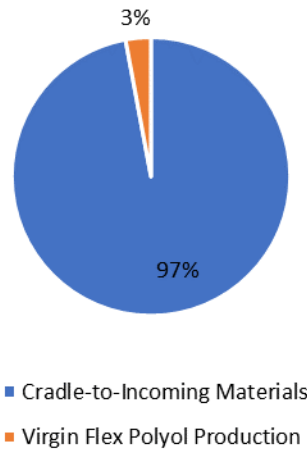


Figure 12. Photochemical Smog Formation Potential for Polyether Polyol for Flexible Foam Polyurethanes

COMPARISON OF 2022 AND 2011 LCI AND LCIA POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANE RESULTS

This section provides a comparison of life cycle inventory and impact assessment category results that were included in the original polyether polyol for flexible foam polyurethane system²⁰ with the current update. These categories include total energy, non-renewable energy, renewable energy, total solid waste, and global warming potential. No comparisons are available for water consumption, solid waste broken out as hazardous and non-hazardous categories, acidification potential, eutrophication potential, photochemical smog formation, or ozone depletion potential. These categories were not included in the original study.

Table 12 shows the comparable LCI and LCIA categories for the 2011 and 2022 polyether polyol results in both English and SI units and includes the percent difference for each category. Percent change between systems is defined as the difference between the 2022 and 2011 totals divided by the 2011 total. The results in Table 12 show a decrease in all category totals. Comparisons of these results have been analyzed in this section focusing on the main differences causing the change in each category. It should be noted that all figures in this section provide the percent change above the comparable bars.

Broadly, differences in the results are due to the use of different or additional companies and manufacturing plants when updating the olefins primary data, the addition of ethylene oxide as an average of more recent primary datasets, and updated data for the polyether polyol plants. Each plant producing the same resin or chemical varies by the amounts of input materials used, fuel types and amounts used, amounts of emissions released, etc. The amalgamation of these changes lead to differences affecting the results. In the updated data,

²⁰ American Chemistry Council, Plastics Division, Cradle-to-Gate Life Cycle Inventory of Nine Plastic Resins and Four Polyurethane Precursors. Prepared by Franklin Associates, A Division of ERG. August, 2011.

polyether polyol and olefins are representative of the years 2015 to 2017. For olefins, some of the same plants provided data; however, some of the plants in the current average were not included in the original data collection in 2004-2006. Additional plants participated in the data collection for this update for the olefins. Also, the number of companies participating in this update for the polyether polyol decreased from 5 to 4, but all four plants provided data in the original and current average. One of the plants included in the original data collection was also included in this data collection albeit as property of a different company and one of the plants from the initial average was closed. The data from all four plants were similar to their original data. The recent collected data included a lower energy amount, which leads to a lower GWP amount.

Table 12. Comparison of 2011 and 2022 LCI and LCIA Results for Polyether Polyol for Flexible Foam Polyurethanes

1000 pounds of Polyether Polyol for Flexible Foam Polyurethane					
<i>LCI Results</i>					<i>LCIA Results</i>
Total Energy	Non-Renewable Energy	Renewable Energy	Total Solid Waste*	Global Warming	
<i>MM Btu</i>	<i>MM Btu</i>	<i>MM Btu</i>	<i>lb</i>	<i>lb CO₂ eq</i>	
Flex Polyol 2022	37.7	37.4	0.33	125	3,205
Flex Polyol 2011	41.2	40.7	0.39	191	4,035
1000 kilograms of Polyether Polyol for Flexible Foam Polyurethane					
<i>LCI Results</i>					<i>LCIA Results</i>
Total Energy	Non-Renewable Energy	Renewable Energy	Total Solid Waste*	Global Warming	
<i>GJ</i>	<i>GJ</i>	<i>GJ</i>	<i>kg</i>	<i>kg CO₂ eq</i>	
Flex Polyol 2022	87.8	87.0	0.76	125	3,205
Flex Polyol 2011	95.7	94.5	0.92	191	4,035
Percent Change	8%	8%	17%	34%	21%

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

ENERGY COMPARISON

Overall, the total energy for polyether polyol has decreased 7.9 GJ on a 1,000 kg basis (3.5 million (MM)Btu/1,000 lb). There is an 8 percent decrease in total energy as compared to the original study's results. When comparing the polyether polyol unit process average energy data, data from the plants that were collected for both studies had small changes with

the electricity amounts decreasing by small amounts. The natural gas used onsite in boilers decreased by almost half, which possibly is due to the use of byproducts onsite from other processes available as fuels at the plants. Figure 13 provides a graphical perspective of the unit processes associated with this energy decrease from the original energy amounts.

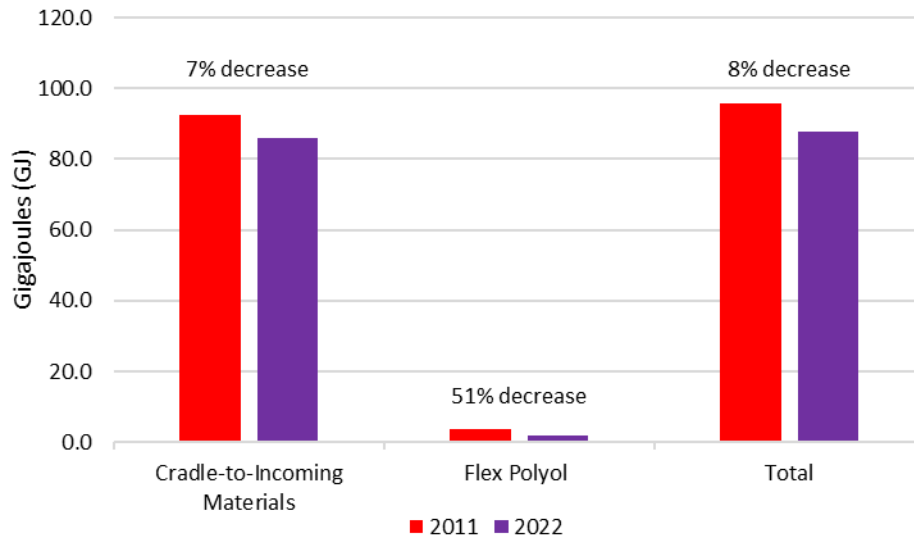


Figure 13. Change in Energy by Stage per 1,000 kg (GJ)

The energy of material resource, which pertains to the amount of inherent energy from the raw materials increased by a small amount for polyether polyol due to the changes in the amount of raw material inputs on compared to the data in the 2011 report. As the amount of material resource energy increased, but the total energy still decreased, it can be concluded that the difference in process energy decreased by a greater percentage than the 8 percent shown in the total. The previous propylene oxide data was reviewed, and the weightings of technologies changed, and the fuel types were updated to the common use of natural gas instead of a mix of natural gas and oil-based fuels, which likely decreased the propylene oxide unit process. However, much of this decrease is due to the energy decreases in the energy requirements for the olefins plants (ethylene and propylene), as well as the oil and natural gas extraction and processing/refining. The energy for converting the raw materials to polyether polyol decreased by over 50 percent compared to the previous energy for this process due to the lower electricity and natural gas use.

The percent difference in renewable energy decreased about 17 percent from the original results. Although this seems quite large, the renewable energy makes up less than one percent of the total energy. Almost all of the renewable energy comes from the production of electricity. The U.S. average electricity grid was used for both the original study and the current update. Of the 2006 electricity grid, approximately 8 percent was created by renewable energy, whereas this renewable energy percentage has almost doubled in 2015

to 15.7 percent. Even though renewable source use has increased in the U.S. average electricity grid, the use of electricity in many of the raw material and intermediate processes required to manufacture polyether polyol has decreased. This decrease in the use of renewable energy is mainly due to decreases in the use of electricity (hydropower and other renewable resources for energy) within all processes required to manufacture polyether polyol.

SOLID WASTE COMPARISON

When compared to the 2011 polyether polyol total solid waste amount, the current polyether polyol study shows 66 kg per 1000 kg polyether polyol less solid waste, which is a 34 percent decrease from the original study. Over 50 percent of the current solid waste amount is due to coal production and combustion from electricity. As the amount of coal used in the electricity grid mix is less than in the previous electricity grid used, plus the amount of electricity use has decreased, it can be concluded that much of this solid waste decrease is due to those decreases. Figure 14 provides a visual of the total solid waste amount split up by the polyether polyol unit process and cradle-to-incoming materials. A decrease occurs for the cradle-to-incoming materials, and a small increase is shown at the polyether polyol plant. Although the solid waste of the plant average did increase by a small amount, the total solid waste is overwhelmed by the decrease in fuel-related solid wastes throughout the cradle-to-gate production. The decrease in cradle-to-incoming materials is a mix of lower amounts of solid waste at the plants, as well as an overall decrease in the electricity use of the olefins plant. Process solid wastes from the natural gas and crude oil production also decreased by small amounts.

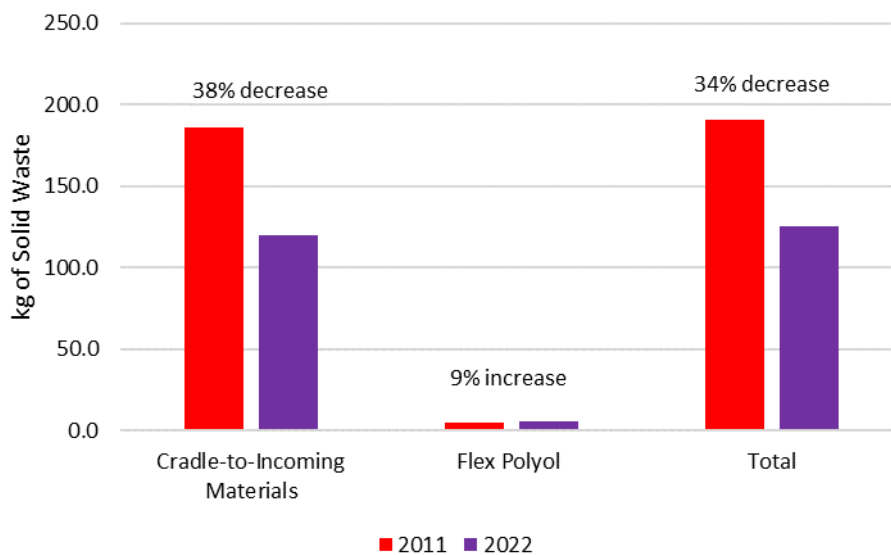


Figure 14. Change in Solid Waste Weight by Unit Process (kg Per 1,000 kg)

GLOBAL WARMING POTENTIAL COMPARISON

The total global warming potential decreased by 830 kg CO₂ equivalents (eq)/1000 kg polyether polyol, which calculates to a 21 percent decrease. Figure 15 displays a column chart with the polyether polyol and cradle-to-incoming materials results that make up the decrease when comparing the 2011 and 2022 GWP results. This overall decrease follows the trend shown in total energy, since much of the greenhouse gases are created from fuel production. The total energy amount includes the material resource energy, which has no greenhouse gases associated with it as it is not combusted.

The GWP specific to the polyether polyol plant decreased by 53 percent, while the energy for the plant also decreased. Due to the fact that the polyether polyol plant GWP amount is only 4 percent of the total GWP amount, the total decrease is more dependent on the cradle-to-incoming materials. The decrease in GWP for the cradle-to-incoming materials comes from decreases in energy use for the raw materials and for the olefins plant. The amount of coal combusted for the US average electricity grid has decreased over time with an increase in natural gas combustion. Coal production and combustion releases higher amounts of greenhouse gases compared to natural gas production and combustion.

It should also be noted that the characterization factors for the GWP have changed since the 2011 report. The methane amount increased from 25 to 28 lb CO₂eq/1 lb methane and the nitrous oxide amount decreased from 298 to 265 lb CO₂eq/1 lb. As the methane and nitrous oxide releases account for less than 10 percent of the GWP characterization, the change in results due to this characterization factor difference is small.

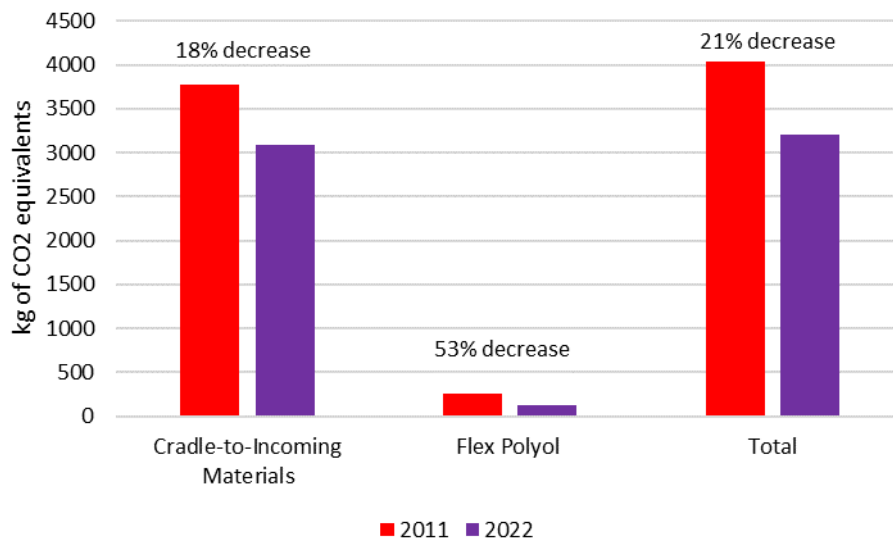


Figure 15. Change in Global Warming Potential by Unit Process (kg of CO₂ eq. per 1,000 kg)

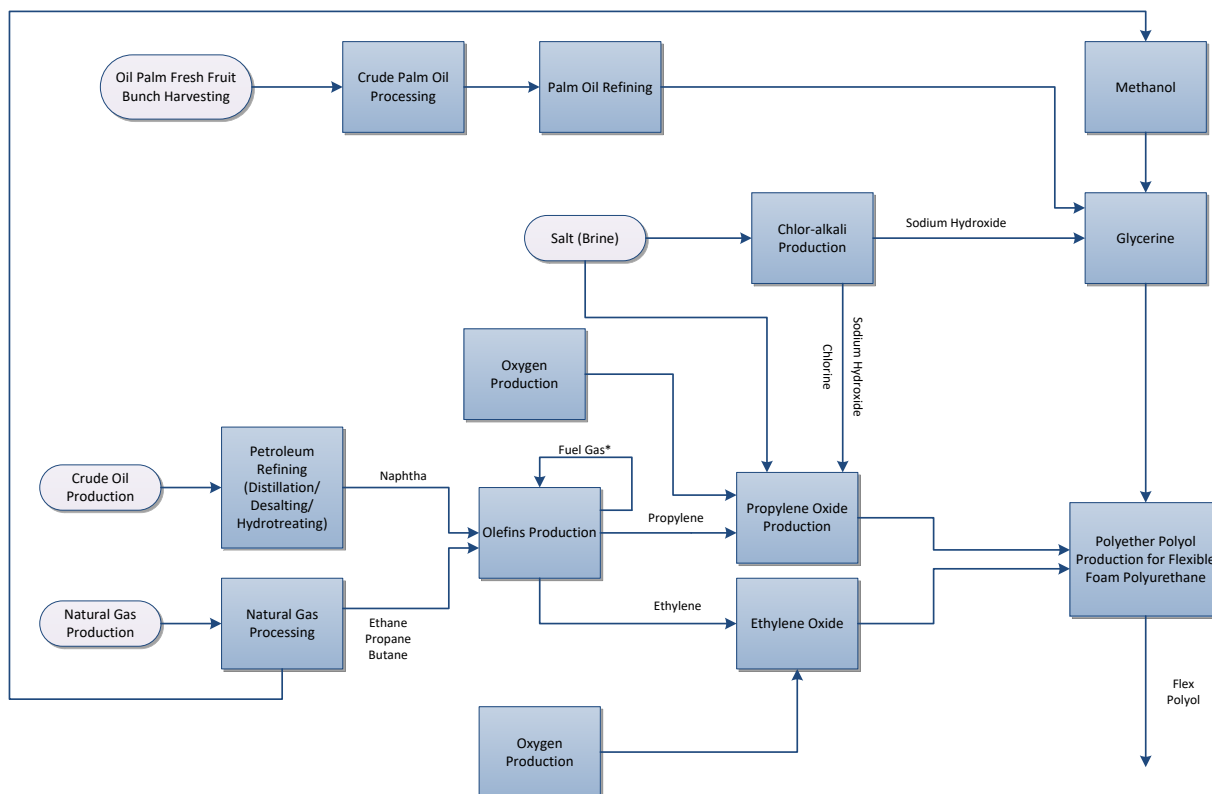
APPENDIX: POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANES MANUFACTURE

This appendix discusses the manufacture of polyether polyol for flexible foam polyurethanes. Polyether polyol is used in a variety of end use applications including polyurethane for cushions in furniture and automobiles, mattress pads and carpet pads. The captured polyether polyol production amount is approximately 90 percent of the polyether polyol production in North America in 2015 (ACC, 2016). This percentage was estimated using the amount of polyol used for flexible foam in the end use table in this document. The material flow for polyether polyol (long chain) for flexible foam polyurethane is shown in Figure 16.

Individual unit process tables on the bases of 1,000 pounds and 1,000 kilograms are also shown within this appendix. The following process is included in this appendix:

- Oil palm fresh fruit cultivation and harvesting
- Crude palm oil processing
- Palm oil refining
- Methanol production
- Glycerine production
- Propylene oxide production
- Ethylene oxide production
- Polyether polyol for flexible foam polyurethanes production

LCI data for olefins (ethylene and propylene), chlor-alkali process (chlorine and sodium hydroxide), ethylene oxide, and polyether polyol production were collected for this update to the U.S. LCI plastics database by member and non-member companies of the American Chemistry Council. Propylene oxide data was not updated from the original 2011 resins report; however, the weighting for the technologies included, as well as the input materials were updated. Updated secondary data was used for crude oil extraction and refining and natural gas production and processing, oil palm fresh fruit cultivation and harvesting, crude palm oil processing, palm oil refining, and glycerine production. Results and LCI data for the production of olefins (ethylene and propylene), oil, and natural gas can be found in the report, *Cradle-to-Gate Life Cycle Analysis of Olefins* (Franklin, 2020). LCI data for the production of chlorine and sodium hydroxide are available in the report, *Cradle-to-Gate Life Cycle Analysis of Polyvinyl Chloride (PVC) Resin* (Franklin, 2021).



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

Figure 16. Flow diagram for the Production of Polyether Polyol for Flexible Foam Polyurethanes.

OIL PALM FRESH FRUIT CULTIVATION AND HARVESTING

Oil palm fruits are primarily grown in Malaysia and Indonesia, which accounted for 84% of global oil palm production in 2019 (FAO, 2019). The fruit is not a high input or land intensive crop when grown in tropical regions. Although, land use change for oil palm cultivation has become a controversial issue in the recent decade due to the environmental effects of land use change of peat swamps. For the current model it is assumed that the oil palm fruits are grown on a pre-existing farm that was not converted from peatland.

Cultivation input data for this model were predominantly based on farm and oil mill survey data (RSPO, 2017), collected from Schmidt and De Rosa, 2020. The cultivation inventory includes aggregated data from both Roundtable on Sustainable Palm Oil (RSPO) certified and noncertified farms in Indonesia and Malaysia. Data on yield, incoming transport, diesel, fertilizers, pesticides, and emissions come from the RSPO survey. The nitrate water emissions reported by Schmidt and De Rosa, 2020 were unusually high so this value was replaced by the nitrate emissions from Omran et al., 2021. No soil carbon sequestration is included in the GWP methodology used for this analysis.

Table 13 shows the inputs, energy, and emissions value for 1,000 pounds and 1,000 kilograms of harvested oil palm fresh fruit bunches.

Table 13. Data for Harvested Oil Palm Fresh Fruit Bunches

	1,000 lb	1,000 kg
Material Inputs		
Ammonium sulfate	1.06 lb	1.06 kg
Urea	3.59 lb	3.59 kg
Phosphate fertilizer	1.82 lb	1.82 kg
Single superphosphate	0.18 lb	0.18 kg
Triple superphosphate	0.35 lb	0.35 kg
Potassium chloride	6.06 lb	6.06 kg
Pesticides, unspecified	0.42 lb	0.42 kg
Energy		
<i>Process Energy</i>		
Diesel	1.00 gal	3.78 l
<i>Transportation Energy</i>		
Truck	32.0 ton·mi	103 tonne·km
Environmental Emissions		
<i>Atmospheric Emissions</i>		
Dinitrogen monoxide	0.47 lb	0.47 kg
Nitric oxide	0.08 lb	0.08 kg
<i>Waterborne Releases</i>		
Nitrate	2.58 lb	2.58 kg
Phosphate	0.18 lb	0.18 kg

Sources: Schmidt and De Rosa, 2020; Omran et al., 2021

CRUDE PALM OIL PROCESSING

After harvesting, oil palm fresh fruit bunches are sent to a palm oil mill for processing. Palm oil mills release effluents such as methane. Palm kernels and empty fruit bunches are the coproducts of the milling process, however empty fruit bunches are not given an allocation in this model because they are a minor coproduct.

Palm kernels are then sent to a palm kernel crusher plant where the kernels are processed into crude palm oil and kernel meal. A mass allocation is used for these two coproducts. Data for milling and crushing were collected from Schmidt and De Rosa, 2020 with small

adjustments and additions where needed. Water consumption at the mill and crusher is based on the value reported by Omran et al., 2021 as the Schmidt and De Rosa, 2020 value did not specify the amount of water consumed out of the process water use.

Table 14 shows the inputs, energy, and emissions value for 1,000 pounds and 1,000 kilograms of crude palm oil.

Table 14. Data for the Production of Crude Palm Oil

	<u>1,000 lb</u>	<u>1,000 kg</u>
Material Inputs		
Oil palm fresh fruit bunches	3906 lb	3906 kg
Energy		
<i>Process Energy</i>		
Diesel	0.56 gal	2.12 l
Electricity from Malaysian grid	96.9 kWh	96.9 kWh
<i>Transportation Energy</i>		
Truck	37.6 ton·mi	121 tonne·km
Environmental Emissions		
<i>Atmospheric Emissions</i>		
Methane, biogenic	40.63 lb	40.63 kg
Dinitrogen monoxide	0.003 lb	0.003 kg
Particulate matter, unspecified	0.5 lb	0.5 kg
Sulfur oxides	0.6 lb	0.6 kg
Nitrogen oxides	0.45 lb	0.45 kg
Ammonia	0.12 lb	0.12
Hydrogen sulfide	0.18 lb	0.18 kg
Water Consumption	499 gal	1890 l

Sources: Schmidt and De Rosa, 2020; Omran et al., 2021

PALM OIL REFINING

Crude palm oil undergoes a refining process where fatty acid distillates and impurities are removed. Energy, transport, material input, and emissions data for refining was obtained from Schmidt and De Rosa, 2020, while water consumption data was collected from Omran et al., 2021.

Table 15 shows the inputs, energy, and emissions values for 1,000 pounds and 1,000 kilograms of refined palm oil.

Table 15. Data for the Production of Refined Palm Oil

	<u>1,000 lb</u>	<u>1,000 kg</u>
Material Inputs		
Crude palm oil	1001 lb	1001 kg
Energy		
<i>Process Energy</i>		
Diesel	0.002 gal	0.007 l
Residual fuel oil	0.002 gal	0.007 l
Electricity from Malaysian grid	96.9 kWh	26.0 kWh
<i>Transportation Energy</i>		
Truck	0.478 ton·mi	1.54 tonne·km
Water Consumption	18.82 gal	71.23 l
Solid Wastes		
Solid Waste, Process to Landfill	12.15 lb	5.51 kg

Sources: Schmidt and De Rosa, 2020; Omran et al., 2021

METHANOL PRODUCTION

Methanol is produced through synthesis of a gaseous mixture of hydrogen, carbon monoxide, and carbon dioxide (called syngas). Methanol can be produced from biomass, coal, heavy oil, naphtha, and renewable or biomass feedstocks. For years, the conventional steam-methane reforming (SMR) technology has been widely used in existing methanol plants (Wang & Huang, 1999).

According to Wang & Huang (1999), the majority of the total natural gas input in methanol plants is used as feed for syngas production; the remainder is used as process fuel. For SMR plants, 78-88% of the total natural gas input in methanol plants is used as feed. The split of natural gas between feed and fuel is used in GREET model to calculate emissions of criteria pollutants during methanol production. In particular, the amount of natural gas burned and the emission factors of natural gas combustion are used to determine combustion emissions of natural gas used as fuel in methanol plants. Because syngas is pressurized in reformers, fugitive emissions of carbon monoxide and carbon dioxide may be released from reformers. But no data are available to estimate this amount. Emissions are estimated from methanol plants using the Fischer-Tropsch Diesel (FTD) production process. According to Syntroleum researchers, VOC emissions from FTD plants should be equal to those from petroleum refineries (on the basis of per-unit-of-product output); carbon monoxide emissions from FTD plants should be fewer than 100 tons per year for a 1,000-barrel-per-day plant; and NOx emissions should be less than 60 tons per year. Using these values and based on an assumed plant capacity of 85%, a carbon monoxide emission rate is estimated to be 58.6 g/million Btu of fuel output and nitrogen oxides emission rate of 35.2 g/million Btu. These emissions rates

are based on manufacturer-suggested emissions limits. In the GREET simulation, only half of these estimated emissions rates are assumed.

The inputs and emissions data for methanol are taken from GREET 2017 and the data for hazardous and non-hazardous waste material is taken from an industrial leader in methanol production. The transportation energy was estimated from plant locations.

Table 16 shows the energy and emissions data for the production of 1,000 pounds and 1,000 kilograms of methanol.

Table 16. Data for the Production of Methanol

	1,000 lb	1,000 kg
Material Inputs		
Oxygen	380 lb	380 kg
Natural gas	620 lb	620 kg
Energy		
<i>Process Energy</i>		
Electricity from grid	114 kWh	252 kWh
Natural gas	118 ft ³	7.37 m ³
<i>Transportation Energy</i>		
Pipeline	155 ton-mi	499 tonne-km
Environmental Emissions		
<i>Atmospheric Emissions</i>		
Carbon dioxide, fossil	390 lb	390 kg
VOC, volatile organic compounds	0.50 lb	0.50 kg
Carbon monoxide	0.72 lb	0.72 kg
Nitrogen oxides	1.11 lb	1.11 kg
Particulates, < 10 um	0.26 lb	0.26 kg
Particulates, < 2.5 um	0.26 lb	0.26 kg
Sulfur oxides	0.33 lb	0.33 kg
Methane	4.59 lb	4.59 kg
Nitrogen dioxide	0.010 lb	0.010 kg
Solid Wastes		
Solid Waste, Process to Landfill	0.26 lb	0.26 kg
Solid Waste Sold for Recycling or Reuse	0.21 lb	0.21 kg
Hazardous Waste, Process to Landfill	0.0069 lb	0.0069 kg
Hazardous waste, recovery	0.0085 lb	0.0085 kg
Water Consumption	47.2 gal	394 l

Sources: Methanex 2016, Wang, M., et. al. 2017.

GLYCERINE PRODUCTION

Glycerine is produced by several methods: 1) as a byproduct of soap manufacture, 2) from propylene and chlorine to form allyl chloride, which is converted to dichlorohydrin with hypochlorous acid and then saponified to glycerine with caustic, 3) by isomerization of propylene oxide to allyl alcohol, which is then reacted with peracetic acid, followed by hydrolyzing the glycidol into glycerine, 4) hydrogenation of carbohydrates with a nickel catalyst, and 5) from acrolein and hydrogen peroxide. In this analysis, glycerine is produced using a traditional method as a byproduct of palm oil methyl ester, which is an intermediate in soap production.

Although a number of raw materials (coconut oil, palm oil, soybean oil, etc.) can be used to produce glycerine, palm oil has been chosen in this analysis. Refined palm kernel oil is converted to methyl esters and glycerine by the transesterification of triglycerides. The reaction occurs with excess methanol, a process known as methanolysis, in the presence of a sodium methylate catalyst. The reaction takes place at atmospheric pressure and can be carried out in a batch or continuous process. The yields will be higher (in excess of 99 percent) for the continuous process.

The reaction forms two layers. The bottom layer consists of crude glycerine, soap, methanol, small amounts of methyl ester, and water. The top layer contains the methyl esters.

The first step in refining the glycerine is to distill off the methanol and water. The methanol is dried and recirculated back into the esterification process or used to make sodium methylate. The remaining glycerine mixture is acidulated to separate the fatty acids from the soap. Methyl esters are also separated and the glycerine is dried.

This data provides the energy requirements of the production of glycerine using ecoinvent data (Althaus, 2007) adapted for the U.S. This adaptation includes the conversion of heavy fuel oil use to natural gas using the heating values of the fuels. Sodium hydroxide has been used as a surrogate for potassium hydroxide. Also, the average U.S. electricity grid was used for the stated electricity. No air or water emissions or solid waste data are available for glycerine manufacture. No biogenic carbon storage is included in the GWP methodology used for this analysis.

The material inputs and energy requirements for the production of glycerine are considered confidential due to the adaptation of ecoinvent data.

PROPYLENE OXIDE PRODUCTION

As of 2020, five different processes for the production of propylene oxide are currently in use. These are the chlorohydrin process and hydroperoxidation processes, using either ethylbenzene, isobutene, or methyl tertiary butyl ether (MTBE). The MTBE hydroperoxidation process is approximately the same as the isobutene hydroperoxidation process. The chlorohydrin process is the oldest and is less flexible because it produces only

propylene oxide. The hydroperoxide reactions, however, produce marketable co-products in addition to propylene oxide. The newer technologies include the hydroperoxidation route based on the use of cumene hydroperoxide and the production from hydrogen peroxide. According to EChem (2021), the chlorohydrin process still accounts for approximately 50 percent of the total propylene oxide produced. The newer technologies continue to increase their production, but still remain less than 15 percent of total production, with the hydroperoxidation process making up the rest. Data was unavailable for the newer technologies, so the data used includes only the chlorohydrin and hydroperoxidation routes.

The data in Table 17 represent the energy requirements and environmental emissions for the production of propylene oxide. The energy, environmental emissions and raw materials are based on three datasets from a confidential secondary source from 1992. The energy requirements for the three older technologies were compared to data in a Department of Energy report from 2000. No information was given in the DOE report about the technology or mix of technologies represented by the energy data. These amounts are a weighted average of the three technologies based on an estimated 2020 capacity. The chlorohydrin process generates 50 percent of the propylene oxide, the isobutene hydroperoxidation (including MTBE hydroperoxidation) 33.9 percent, and the ethylbenzene hydroperoxidation 16.1 percent (ECHEMI, 2021 and Nexant, 2009). No data was available for two newer technologies that make up approximately 10 percent in the estimated 2020 capacity. In the two hydroperoxidation datasets, coproduct credit was given on a mass basis.

The chlorohydrin process begins with an equal molar mixture of propylene and chlorine in water, which forms the solution propylene chlorohydrin. The chlorohydrin solution is treated with a base, usually cell liquor from a chlorine plant, to form the oxide. Propylene oxide is then stripped from the alkaline solution and purified by distilling the light ends, then the oxide.

In the isobutene hydroperoxide process, propylene oxide and tert-butyl alcohol are formed from isobutene, oxygen, and propylene. Isobutane is first oxidized to the intermediate, tert-butyl hydroperoxide. This intermediate and an alcohol mixture coproduct is combined with propylene. This is reacted to nearly 100 percent conversion of the hydroperoxide over a catalyst. The products stream contains propylene oxide and tert-butyl alcohol. The products are separated in distillation columns.

In the ethylbenzene hydroperoxide reaction, propylene oxide and styrene are produced. Ethylbenzene and oxygen are reacted to form ethylbenzene hydroperoxide and small amounts of methylbenzyl alcohol and acetophenone. This solution and propylene are fed to the epoxidation reactor. The products stream contains propylene oxide, propylene, methylbenzyl alcohol, and small amounts of several other hydrocarbons. Propylene oxide is purified by a multi-tower distillation scheme.

Table 17. Data for the Production of Propylene Oxide

	<u>1,000 lb</u>	<u>1,000 kg</u>
Material Inputs		
Propylene	787 lb	787 kg
Sodium Chloride	1,117 lb	1,117 kg
Chlorine	680 lb	680 kg
Sodium Hydroxide	791 lb	791 kg
Oxygen	46 lb	46 kg
Energy		
<i>Process Energy</i>		
Electricity from grid	114 kWh	251 kWh
Natural gas	4,202 ft ³	262 m ³
<i>Transportation Energy</i>		
Barge		
Pipeline -refinery products	1.17 ton-mi	3.76 tonne-km
Pipeline -natural gas products	121 ton-mi	390 tonne-km
Truck	0.050 ton-mi	0.16 tonne-km
Rail	83.9 ton-mi	270 tonne-km
Environmental Emissions		
Atmospheric Emissions		
Acetic acid	0.0040 lb	0.0040 kg
Ammonia	0.072 lb	0.072 kg
Carbon dioxide, fossil	14 lb	14 kg
Chlorine	1.5E-04 lb	1.5E-04 kg
Benzene, ethyl-	1.40 lb	1.40 kg
NMVOG, non-methane volatile organic compounds, unspecified origin	3.40 lb	3.40 kg
Propylene oxide	0.69 lb	0.69 kg
Formic acid	0.062 lb	0.062 kg
Propylene	0.18 lb	0.18 kg
Isobutane	0.96 lb	0.96 kg
<i>Waterborne Releases</i>		
Acids, unspecified	2.3 lb	2.3 kg
Hydrocarbons, unspecified	3.3 lb	3.3 kg
Phenols, unspecified	1.9 lb	1.9 kg
Sodium hydroxide	2.1 lb	2.1 kg
Acetic acid	3.1 lb	3.1 kg
Formic acid	2.7 lb	2.7 kg
Solid Wastes		
Solid waste, process to landfill	0.22 lb	0.22 kg

Sources: US DOE, 2000; Franklin, 1993; EChem, 2021; and Nexant, 2009.

ETHYLENE OXIDE PRODUCTION

The primary production method for ethylene oxide is the direct, vapor-phase oxidation of ethylene with air or oxygen over a catalyst at a high temperature and pressure (DOW, 2009). The predominant feed for commercial oxidation processes is oxygen rather than air due to higher yields and less downtime (GCI, 2010). While most manufacturers of ethylene oxide purchase the oxygen needed in the reaction, some plants pull oxygen from air separation on-site. The ethylene oxide is catalyzed by silver and is exothermic. Oil or boiling water is used to absorb the heat in a multi-tubular catalytic reactor and produce steam that is used in other parts of the process. The products of the reaction are fed to an ethylene oxide absorber for lights removal by water quenching. Part of the gaseous stream is recycled into the multi-tubular reactor, while the other part is sent to a CO₂ removal unit consisting of an absorber and a stripper (Chem, 2015). Because of its special molecular structure, ethylene oxide easily participates in the addition reaction and can easily polymerize into larger compounds (GCI, 2010).

A disadvantage to the oxidation process is the conversion of ethylene to carbon dioxide at a ratio of 6:2 (GCI, 2010) and water, which is released to the environment. However, excess ethylene is added to prevent additional oxidation of the ethylene oxide that would increase the production of carbon dioxide. This creates typical conversion rates for ethylene-to-ethylene oxide of only 10 to 20 percent per pass. Approximately 20 to 25 percent of the ethylene is broken down to carbon dioxide and water. Additionally, gases from the catalytic reaction are cooled and then passed through a scrubber where the ethylene oxide is absorbed as a dilute aqueous solution. This process includes the removal of CO₂ using physical sorbents, the Hot Potassium Carbonate process, or cryogenic separation techniques (GCI, 2010)

The energy requirements and environmental emissions for the production of ethylene oxide are provided as a system process (cradle-to-ethylene oxide) in Table 18. Ethylene oxide is produced in plants that manufacture several other products within the same unit. Some plants were not able to separate the ethylene oxide emissions from the other processes manufactured at the ethylene oxide plant and so ethylene oxide emissions may be minorly overstated. These data include a weighted average of 2 ethylene oxide producers with 4 plants in the U.S. from 2015. The source stated is for the ethylene oxide data only. Sources for cradle-to-olefins and oxygen are stated in previously released reports.

Table 18. Data for the Life Cycle Inventory of Ethylene Oxide

	1,000 lb	1,000 kg
Material Inputs/Energy Inputs		
Corn seed	683 lb	683 kg
Limestone	0.0043 lb	0.0043 kg
Oxygen	620 lb	620 kg
Phosphate ore	0.034 lb	0.034 kg
Sylvinite and Brines	0.017 lb	0.017 kg
Trona	0.012 lb	0.012 kg
Unprocessed bituminous coal, in ground	45.4 lb	45.4 kg
Unprocessed lignite	5.97 lb	5.97 kg
Oil, crude	15.6 lb	15.6 kg
Gas, natural/m3	9,147 ft ³	571 m ³
Uranium oxide, 332 GJ per kg, in ore	289 Thousand Btu	673 MJ
Gas, natural, 48.68 MJ per kg, in ground (EMR)	15,671 Thousand Btu	36,450 MJ
Oil, crude, 43.66 MJ per kg, in ground (EMR)	1,582 Thousand Btu	3,680 MJ
Energy, recovered	256 Thousand Btu	596 MJ
Energy, from gas, natural	9.51 Thousand Btu	22.1 MJ
Energy, from biomass	294 Thousand Btu	683 MJ
Energy, from hydro power	30.7 Thousand Btu	71.3 MJ
Energy, geothermal	1.86 Thousand Btu	4.32 MJ
Energy, kinetic (in wind), converted	26.6 Thousand Btu	62.0 MJ
Energy, solar, converted	4.22 Thousand Btu	9.81 MJ
Energy, unspecified	2.30 Thousand Btu	5.36 MJ
Environmental Emissions		
<i>Atmospheric Emissions</i>		
1-Butanol	7.5E-08 lb	7.5E-08 kg
1-Methyl-2-pyrrolidinone	3.9E-07 lb	3.9E-07 kg
1-Methylnaphthalene	1.7E-08 lb	1.7E-08 kg
1,2,3,4,7,8,9 Heptachlorodibenzofuran	1.3E-13 lb	1.3E-13 kg
1,2,3,6,7,8-Hexachlorodibenzo-p-dioxin	5.0E-14 lb	5.0E-14 kg
1,2,3,7,8-Pentachlorodibenzo-p-dioxin	3.2E-14 lb	3.2E-14 kg
1,4-Dioxane	1.0E-08 lb	1.0E-08 kg
2-Chloroacetophenone	9.1E-11 lb	9.1E-11 kg
3-Methylcholanthrene	8.2E-12 lb	8.2E-12 kg
4-Dimethylaminoazobenzene	5.3E-10 lb	5.3E-10 kg
4-Methyl-2-methoxyphenol	3.1E-09 lb	3.1E-09 kg
4-Methyl-2-pentanone	2.0E-05 lb	2.0E-05 kg
4,4'-Diisocyanatodiphenylmethane	8.1E-09 lb	8.1E-09 kg
4,4'-Methylenebisbenzeneamine	2.7E-09 lb	2.7E-09 kg
5-methyl Chrysene	4.9E-10 lb	4.9E-10 kg
7,12-Dimethylbenz(a)anthracene	4.6E-11 lb	4.6E-11 kg
Acenaphthene	1.3E-08 lb	1.3E-08 kg
Acenaphthylene	2.2E-08 lb	2.2E-08 kg
Acetaldehyde	2.0E-04 lb	2.0E-04 kg
Acetamide	8.6E-11 lb	8.6E-11 kg

Table 18. Data for the Life Cycle Inventory of Ethylene Oxide (Continued)

	1,000 lb	1,000 kg
Acetonitrile	7.6E-07 lb	7.6E-07 kg
Acetophenone	6.2E-08 lb	6.2E-08 kg
Acrolein	1.6E-04 lb	1.6E-04 kg
Acrylamide	3.0E-12 lb	3.0E-12 kg
Acrylonitrile	2.0E-09 lb	2.0E-09 kg
Aldehydes, unspecified	0.0088 lb	0.0088 kg
Ammonia	0.0024 lb	0.0024 kg
Ammonium chloride	1.1E-04 lb	1.1E-04 kg
Aniline	9.3E-08 lb	9.3E-08 kg
Anthracene	1.3E-08 lb	1.3E-08 kg
Antimony	1.1E-06 lb	1.1E-06 kg
Arsenic	1.0E-05 lb	1.0E-05 kg
Arsenic, ion	1.7E-07 lb	1.7E-07 kg
Asbestos	7.6E-11 lb	7.6E-11 kg
Barium	4.4E-10 lb	4.4E-10 kg
Barium compounds	1.9E-08 lb	1.9E-08 kg
Benz(a)acridine	7.3E-12 lb	7.3E-12 kg
Benzene	0.0024 lb	0.0024 kg
Benzene, 1,2,4-trichloro-	9.2E-10 lb	9.2E-10 kg
Benzene, 1,2,4-trimethyl-	2.1E-05 lb	2.1E-05 kg
Benzene, 1,4-dichloro-	1.6E-07 lb	1.6E-07 kg
Benzene, chloro-	7.8E-07 lb	7.8E-07 kg
Benzene, ethyl-	2.0E-04 lb	2.0E-04 kg
Benzene, hexachloro-	9.2E-10 lb	9.2E-10 kg
Benzidine	9.8E-09 lb	9.8E-09 kg
Benzidine, 3,3'-dichloro-	9.2E-10 lb	9.2E-10 kg
Benzidine, 3,3'-dimethoxy-	6.4E-09 lb	6.4E-09 kg
Benzidine, 3,3'-dimethyl-	4.5E-09 lb	4.5E-09 kg
Benzo(a)anthracene	2.4E-08 lb	2.4E-08 kg
Benzo(a)pyrene	1.1E-06 lb	1.1E-06 kg
Benzo(b)fluoranthene	1.8E-09 lb	1.8E-09 kg
Benzo(b,j,k)fluoranthene	2.4E-09 lb	2.4E-09 kg
Benzo(e)pyrene	3.1E-10 lb	3.1E-10 kg
Benzo(g,h,i)perylene	3.1E-07 lb	3.1E-07 kg
Benzo(k)fluoranthene	9.1E-10 lb	9.1E-10 kg
Benzofluoranthene	5.2E-10 lb	5.2E-10 kg
Benzyl chloride	9.1E-09 lb	9.1E-09 kg
Beryllium	5.7E-07 lb	5.7E-07 kg
Biphenyl	1.8E-06 lb	1.8E-06 kg
Bis(2-chloroethyl)ether	9.2E-10 lb	9.2E-10 kg
Bisphenol A	5.7E-07 lb	5.7E-07 kg
Boron carbide	1.5E-07 lb	1.5E-07 kg
Bromoform	5.1E-10 lb	5.1E-10 kg
Butadiene	3.9E-05 lb	3.9E-05 kg
Butadiene, hexachloro-	9.2E-10 lb	9.2E-10 kg
Butane, 1,2-epoxy-	1.7E-08 lb	1.7E-08 kg
Cadmium	7.9E-06 lb	7.9E-06 kg

Table 18. Data for the Life Cycle Inventory of Ethylene Oxide (Continued)

	1,000 lb	1,000 kg
Carbon dioxide, fossil	1,724 lb	1,724 kg
Carbon disulfide	4.1E-06 lb	4.1E-06 kg
Carbon monoxide	0.91 lb	0.91 kg
Carbonyl sulfide	3.1E-05 lb	3.1E-05 kg
Chlorine	1.2E-05 lb	1.2E-05 kg
Chloroform	1.2E-06 lb	1.2E-06 kg
Chromium	1.4E-05 lb	1.4E-05 kg
Chromium III	3.5E-07 lb	3.5E-07 kg
Chromium VI	1.9E-06 lb	1.9E-06 kg
Chrysene	1.2E-08 lb	1.2E-08 kg
Cobalt	3.4E-06 lb	3.4E-06 kg
Copper	6.9E-08 lb	6.9E-08 kg
Copper compounds	1.2E-07 lb	1.2E-07 kg
Cresol	2.5E-06 lb	2.5E-06 kg
Cumene	1.1E-05 lb	1.1E-05 kg
Cyanamide	7.1E-05 lb	7.1E-05 kg
Cyanide	3.2E-08 lb	3.2E-08 kg
Cyclohexane	2.8E-05 lb	2.8E-05 kg
Cyclopentadiene, hexachloro-	9.2E-10 lb	9.2E-10 kg
Dibenz(a,h)anthracene	1.2E-09 lb	1.2E-09 kg
Dibenzofuran	2.8E-09 lb	2.8E-09 kg
Dibenzofuran, 1,2,3,4,6,7,8-heptachloro-	5.6E-13 lb	5.6E-13 kg
Dibenzofuran, 1,2,3,4,6,7,8,9-octachloro-	1.6E-13 lb	1.6E-13 kg
Dibenzofuran, 1,2,3,4,7,8-hexachloro-	1.9E-13 lb	1.9E-13 kg
Dibenzofuran, 1,2,3,6,7,8-hexachloro-	2.0E-13 lb	2.0E-13 kg
Dibenzofuran, 1,2,3,7,8-pentachloro-	1.4E-13 lb	1.4E-13 kg
Dibenzofuran, 1,2,3,7,8,9-hexachloro-	1.2E-13 lb	1.2E-13 kg
Dibenzofuran, 2,3,4,6,7,8-hexachloro-	1.9E-13 lb	1.9E-13 kg
Dibenzofuran, 2,3,4,7,8-pentachloro-	1.7E-13 lb	1.7E-13 kg
Dibenzofuran, 2,3,7,8-tetrachloro-	1.2E-13 lb	1.2E-13 kg
Dicyclopentadiene	1.7E-07 lb	1.7E-07 kg
Diethanolamine	5.6E-06 lb	5.6E-06 kg
Diethylene Ether	8.6E-06 lb	8.6E-06 kg
Diisobutyl ketone	4.0E-07 lb	4.0E-07 kg
Dimethyl formamide	3.7E-10 lb	3.7E-10 kg
Dinitrogen monoxide	0.0096 lb	0.0096 kg
Dioxin, 1,2,3,4,6,7,8-heptachlorodibenzo-p-	1.5E-13 lb	1.5E-13 kg
Dioxin, 1,2,3,4,6,7,8,9-octachlorodibenzo-p-	2.2E-13 lb	2.2E-13 kg
Dioxin, 1,2,3,4,7,8-hexachlorodibenzo-p-	3.3E-14 lb	3.3E-14 kg
Dioxin, 1,2,3,7,8,9-hexachlorodibenzo-	4.1E-14 lb	4.1E-14 kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	1.7E-11 lb	1.7E-11 kg
Dioxins (unspecified)	5.3E-13 lb	5.3E-13 kg
Epichlorohydrin	6.6E-07 lb	6.6E-07 kg
Ethane	9.4E-04 lb	9.4E-04 kg
Ethane, 1,1-dichloro-	5.3E-07 lb	5.3E-07 kg
Ethane, 1,1,1-trichloro-, HCFC-140	1.2E-06 lb	1.2E-06 kg

Table 18. Data for the Life Cycle Inventory of Ethylene Oxide (Continued)

	1,000 lb	1,000 kg
Ethane, 1,1,2-trichloro-	7.1E-07 lb	7.1E-07 kg
Ethane, 1,1,2,2-tetrachloro-	1.2E-06 lb	1.2E-06 kg
Ethane, 1,2-dibromo-	1.2E-06 lb	1.2E-06 kg
Ethane, 1,2-dichloro-	1.5E-07 lb	1.5E-07 kg
Ethane, chloro-	7.6E-09 lb	7.6E-09 kg
Ethane, hexachloro-	9.2E-10 lb	9.2E-10 kg
Ethanol, 2-ethoxy-	6.3E-13 lb	6.3E-13 kg
Ethanol, 2-methoxy-	4.6E-08 lb	4.6E-08 kg
Ethanol, 2-propoxy-	4.6E-09 lb	4.6E-09 kg
Ethene	0.030 lb	0.030 kg
Ethene, 1,1-dichloro-	1.1E-10 lb	1.1E-10 kg
Ethene, chloro-	3.9E-07 lb	3.9E-07 kg
Ethene, tetrachloro-	3.6E-06 lb	3.6E-06 kg
Ethene, trichloro-	5.3E-07 lb	5.3E-07 kg
Ethylene glycol	1.5E-06 lb	1.5E-06 kg
Ethylene oxide	0.0060 lb	0.0060 kg
Fluoranthene	9.0E-08 lb	9.0E-08 kg
Fluorene	2.8E-08 lb	2.8E-08 kg
Fluoride	2.9E-06 lb	2.9E-06 kg
Fluorine	9.3E-09 lb	9.3E-09 kg
Formaldehyde	0.0020 lb	0.0020 kg
Furan	9.5E-11 lb	9.5E-11 kg
Glycidol	3.5E-09 lb	3.5E-09 kg
Glycol ethers	1.1E-06 lb	1.1E-06 kg
Hexane	3.0E-04 lb	3.0E-04 kg
Hexane, 1,6-diisocyanato-	5.3E-09 lb	5.3E-09 kg
Hydrazine	4.4E-11 lb	4.4E-11 kg
Hydrazine, methyl-	2.2E-09 lb	2.2E-09 kg
Hydrocarbons, aromatic	1.5E-06 lb	1.5E-06 kg
Hydrocarbons, unspecified	7.1E-04 lb	7.1E-04 kg
Hydrogen chloride	0.027 lb	0.027 kg
Hydrogen cyanide	2.2E-04 lb	2.2E-04 kg
Hydrogen fluoride	0.0033 lb	0.0033 kg
Hydrogen sulfide	1.1E-04 lb	1.1E-04 kg
Indeno(1,2,3-cd)pyrene	4.1E-09 lb	4.1E-09 kg
Isophorone	8.9E-09 lb	8.9E-09 kg
Isoprene	4.9E-07 lb	4.9E-07 kg
Kerosene	5.2E-05 lb	5.2E-05 kg
Lead	1.3E-05 lb	1.3E-05 kg
m-Cresol	3.8E-09 lb	3.8E-09 kg
m-Xylene	3.3E-08 lb	3.3E-08 kg
Magnesium	2.4E-04 lb	2.4E-04 kg
Manganese	1.4E-05 lb	1.4E-05 kg
Mercaptans, unspecified	2.6E-06 lb	2.6E-06 kg
Mercury	3.5E-06 lb	3.5E-06 kg
Methane	2.07 lb	2.07 kg

Table 18. Data for the Life Cycle Inventory of Ethylene Oxide (Continued)

	1,000 lb	1,000 kg
Methane, bromo-, Halon 1001	3.8E-07 lb	3.8E-07 kg
Methane, chlorodifluoro-, HCFC-22	1.1E-06 lb	1.1E-06 kg
Methane, dichloro-, HCC-30	1.1E-05 lb	1.1E-05 kg
Methane, fossil	4.92 lb	4.92 kg
Methane, monochloro-, R-40	1.2E-08 lb	1.2E-08 kg
Methane, tetrachloro-, CFC-10	8.1E-07 lb	8.1E-07 kg
Methanol	2.9E-04 lb	2.9E-04 kg
Methyl ethyl ketone	5.1E-09 lb	5.1E-09 kg
Methyl methacrylate	2.6E-10 lb	2.6E-10 kg
Molybdenum trioxide	1.2E-07 lb	1.2E-07 kg
N-Nitrosodimethylamine	9.2E-10 lb	9.2E-10 kg
Naphthalene	2.3E-05 lb	2.3E-05 kg
Naphthalene, 2-methyl-	4.3E-08 lb	4.3E-08 kg
Naphthalene, beta-chloro-	6.5E-15 lb	6.5E-15 kg
Nickel	3.2E-05 lb	3.2E-05 kg
Nickel refinery dust	2.1E-12 lb	2.1E-12 kg
Nitrobenzene	1.7E-08 lb	1.7E-08 kg
Nitrogen dioxide	6.5E-04 lb	6.5E-04 kg
Nitrogen oxides	4.44 lb	4.44 kg
Nitrous oxide	0.16 lb	0.16 kg
NMHC, non-methane hydrocarbons	0.038 lb	0.038 kg
NMVOC, non-methane volatile organic compounds, unspecified origin	0.21 lb	0.21 kg
o-Cresol	3.5E-14 lb	3.5E-14 kg
o-Toluidine	1.8E-09 lb	1.8E-09 kg
o-Xylene	6.8E-08 lb	6.8E-08 kg
Organic acids	4.0E-07 lb	4.0E-07 kg
Organic substances, unspecified	1.6E-04 lb	1.6E-04 kg
Ozone	3.7E-06 lb	3.7E-06 kg
p-Phenylenediamine	3.9E-09 lb	3.9E-09 kg
p-Xylene	4.9E-08 lb	4.9E-08 kg
PAH, polycyclic aromatic hydrocarbons	2.3E-06 lb	2.3E-06 kg
Particulates	2.7E-07 lb	2.7E-07 kg
Particulates, < 10 um	0.055 lb	0.055 kg
Particulates, < 2.5 um	0.078 lb	0.078 kg
Particulates, > 10 um	1.7E-07 lb	1.7E-07 kg
Particulates, > 2.5 um, and < 10um	0.019 lb	0.019 kg
Particulates, unspecified	0.11 lb	0.11 kg
Pentane, 2,2,4-trimethyl-	3.3E-05 lb	3.3E-05 kg
Perylene	1.9E-12 lb	1.9E-12 kg
Phenanthrene	8.4E-07 lb	8.4E-07 kg
Phenol	8.7E-06 lb	8.7E-06 kg
Phenol, 2,4-dimethyl-	1.8E-08 lb	1.8E-08 kg
Phenol, 2,4-dinitro-	9.2E-10 lb	9.2E-10 kg
Phenol, 2,4,5-trichloro-	9.2E-10 lb	9.2E-10 kg
Phenol, 2,4,6-trichloro-	1.0E-09 lb	1.0E-09 kg
Phenol, 4-nitro-	9.2E-10 lb	9.2E-10 kg

Table 18. Data for the Life Cycle Inventory of Ethylene Oxide (Continued)

	1,000 lb	1,000 kg
Phenol, pentachloro-	2.0E-09 lb	2.0E-09 kg
Phenols, unspecified	8.6E-07 lb	8.6E-07 kg
Phosphorus	3.2E-06 lb	3.2E-06 kg
Phthalate, dibutyl-	2.6E-08 lb	2.6E-08 kg
Phthalate, dimethyl-	9.2E-10 lb	9.2E-10 kg
Phthalate, dioctyl-	3.5E-08 lb	3.5E-08 kg
Polychlorinated biphenyls	5.4E-11 lb	5.4E-11 kg
Propanal	5.8E-07 lb	5.8E-07 kg
Propane, 1,2-dichloro-	6.0E-07 lb	6.0E-07 kg
Propane, 2-nitro-	8.7E-09 lb	8.7E-09 kg
Propene	1.4E-04 lb	1.4E-04 kg
Propene, 1,3-dichloro-	5.9E-07 lb	5.9E-07 kg
Propylene oxide	3.2E-08 lb	3.2E-08 kg
Pyrene	1.1E-07 lb	1.1E-07 kg
Quinoline	1.7E-09 lb	1.7E-09 kg
Radionuclides (Including Radon)	0.0029 lb	0.0029 kg
Selenium	2.9E-05 lb	2.9E-05 kg
Styrene	2.6E-06 lb	2.6E-06 kg
Sulfur dioxide	0.67 lb	0.67 kg
Sulfur oxides	0.53 lb	0.53 kg
Sulfuric acid	2.4E-04 lb	2.4E-04 kg
Sulfuric acid, dimethyl ester	6.2E-10 lb	6.2E-10 kg
t-Butyl alcohol	2.0E-08 lb	2.0E-08 kg
t-Butyl methyl ether	3.1E-06 lb	3.1E-06 kg
Tar	1.7E-08 lb	1.7E-08 kg
TOC, Total Organic Carbon	0.0017 lb	0.0017 kg
Toluene	0.0017 lb	0.0017 kg
Toluene, 2,4-dinitro-	9.2E-10 lb	9.2E-10 kg
Vanadium	1.1E-09 lb	1.1E-09 kg
Vanadium compounds	2.3E-07 lb	2.3E-07 kg
Vinyl acetate	8.5E-09 lb	8.5E-09 kg
VOC, volatile organic compounds	0.65 lb	0.65 kg
Xylene	5.5E-04 lb	5.5E-04 kg
Zinc	3.1E-08 lb	3.1E-08 kg
Zinc compounds	2.8E-06 lb	2.8E-06 kg

Table 18. Data for the Life Cycle Inventory of Ethylene Oxide (Continued)

	<u>1,000 lb</u>	<u>1,000 kg</u>
<i>Waterborne Releases</i>		
1-Methyl-2-pyrrolidinone	1.5E-09 lb	1.5E-09 kg
1,2,3,6,7,8-Hexachlorodibenzo-p-dioxin	5.2E-15 lb	5.2E-15 kg
1,2,3,7,8-Pentachlorodibenzo-p-dioxin	4.0E-15 lb	4.0E-15 kg
3-Methylcholanthrene	8.0E-07 lb	8.0E-07 kg
4-Methyl-2-pentanone	2.3E-09 lb	2.3E-09 kg
7,12-Dimethylbenz(a)anthracene	8.0E-06 lb	8.0E-06 kg
Acenaphthene	7.7E-11 lb	7.7E-11 kg
Acenaphthylene	7.7E-11 lb	7.7E-11 kg
Acetonitrile	3.8E-08 lb	3.8E-08 kg
Acidity, unspecified	4.5E-05 lb	4.5E-05 kg
Acids, unspecified	3.0E-12 lb	3.0E-12 kg
Aluminium	8.5E-04 lb	8.5E-04 kg
Ammonia	8.4E-04 lb	8.4E-04 kg
Ammonium, ion	2.3E-05 lb	2.3E-05 kg
Anthracene	6.6E-09 lb	6.6E-09 kg
Antimony compounds	2.2E-07 lb	2.2E-07 kg
Arsenic	7.0E-07 lb	7.0E-07 kg
Barium	0.17 lb	0.17 kg
Barium compounds	2.9E-07 lb	2.9E-07 kg
Benzene	0.0080 lb	0.0080 kg
Benzene, 1,2,4-trimethyl-	7.0E-08 lb	7.0E-08 kg
Benzene, ethyl-	8.0E-04 lb	8.0E-04 kg
Benzo(a)anthracene	3.1E-09 lb	3.1E-09 kg
Benzo(a)pyrene	3.1E-09 lb	3.1E-09 kg
Benzo(g,h,i)perylene	8.9E-09 lb	8.9E-09 kg
Benzo(k)fluoranthene	7.7E-11 lb	7.7E-11 kg
Bicarbonate, ion	1.19 lb	1.19 kg
Biphenyl	8.0E-04 lb	8.0E-04 kg
BOD5, Biological Oxygen Demand	0.13 lb	0.13 kg
Boron	8.6E-04 lb	8.6E-04 kg
Bromide	1.7E-08 lb	1.7E-08 kg
Butadiene	8.0E-04 lb	8.0E-04 kg
Cadmium	3.5E-07 lb	3.5E-07 kg
Cadmium compounds	1.1E-10 lb	1.1E-10 kg
Calcium	0.13 lb	0.13 kg
Carbon disulfide	1.1E-07 lb	1.1E-07 kg
Chloride	1.78 lb	1.78 kg
Chlorine	2.9E-08 lb	2.9E-08 kg
Chromium	3.5E-08 lb	3.5E-08 kg
Chromium compounds	2.5E-08 lb	2.5E-08 kg
Chromium III	2.8E-08 lb	2.8E-08 kg
Chromium VI	7.7E-08 lb	7.7E-08 kg
Chrysene	1.8E-09 lb	1.8E-09 kg
Cobalt compounds	6.8E-08 lb	6.8E-08 kg

Table 18. Data for the Life Cycle Inventory of Ethylene Oxide (Continued)

	1,000 lb	1,000 kg
COD, Chemical Oxygen Demand	0.32 lb	0.32 kg
Copper	2.1E-05 lb	2.1E-05 kg
Copper compounds	3.9E-08 lb	3.9E-08 kg
Cresol	8.1E-06 lb	8.1E-06 kg
Cumene	4.1E-08 lb	4.1E-08 kg
Cyanamide	4.4E-08 lb	4.4E-08 kg
Cyanide	8.0E-07 lb	8.0E-07 kg
Cyclohexane	3.7E-08 lb	3.7E-08 kg
Dibenz(a,h)anthracene	1.8E-09 lb	1.8E-09 kg
Dibenz(a,j)acridine	8.0E-07 lb	8.0E-07 kg
Dibenzofuran, 1,2,3,4,6,7,8-heptachloro-	4.1E-14 lb	4.1E-14 kg
Dibenzofuran, 1,2,3,4,7,8-hexachloro-	3.3E-14 lb	3.3E-14 kg
Dibenzofuran, 2,3,4,6,7,8-hexachloro-	5.4E-15 lb	5.4E-15 kg
Dibenzofuran, 2,3,4,7,8-pentachloro-	7.8E-15 lb	7.8E-15 kg
Dibenzofuran, 2,3,7,8-tetrachloro-	3.5E-15 lb	3.5E-15 kg
Diethanolamine	5.9E-08 lb	5.9E-08 kg
Dimethyl phthalate	8.0E-05 lb	8.0E-05 kg
Dioxin, 1,2,3,7,8,9-hexachlorodibenzo-	4.9E-15 lb	4.9E-15 kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	1.7E-15 lb	1.7E-15 kg
Dissolved solids	12.0 lb	12.0 kg
Ethanol, 2-ethoxy-	2.1E-08 lb	2.1E-08 kg
Ethene	0.0080 lb	0.0080 kg
Ethylene glycol	8.0E-04 lb	8.0E-04 kg
Ethylene oxide	7.0E-05 lb	7.0E-05 kg
Fluorene	7.7E-11 lb	7.7E-11 kg
Fluoride	3.7E-04 lb	3.7E-04 kg
Hydrocarbons, aromatic	1.5E-05 lb	1.5E-05 kg
Hydrocarbons, unspecified	0.012 lb	0.012 kg
Hydrogen fluoride	6.1E-10 lb	6.1E-10 kg
Hydrogen sulfide	1.3E-06 lb	1.3E-06 kg
Iron	0.0023 lb	0.0023 kg
Isoprene	8.0E-05 lb	8.0E-05 kg
Lead	3.0E-06 lb	3.0E-06 kg
Lead compounds	1.1E-07 lb	1.1E-07 kg
m-Xylene	2.1E-09 lb	2.1E-09 kg
Magnesium	0.022 lb	0.022 kg
Manganese	0.0092 lb	0.0092 kg
Manganese compounds	9.4E-08 lb	9.4E-08 kg
Mercury	1.1E-07 lb	1.1E-07 kg
Mercury compounds	4.2E-09 lb	4.2E-09 kg
Metallic ions, unspecified	6.4E-08 lb	6.4E-08 kg
Methanol	3.7E-06 lb	3.7E-06 kg
Molybdenum trioxide	2.2E-07 lb	2.2E-07 kg
Naphthalene	1.0E-07 lb	1.0E-07 kg
Naphthalene, 2-methyl-	2.2E-09 lb	2.2E-09 kg
Nickel	8.0E-07 lb	8.0E-07 kg
Nickel compounds	5.6E-07 lb	5.6E-07 kg
Nitrate compounds	0.0012 lb	0.0012 kg

Table 18. Data for the Life Cycle Inventory of Ethylene Oxide (Continued)

	1,000 lb	1,000 kg
Nitrogen	0.0012 lb	0.0012 kg
Nitrogen, total	0.0057 lb	0.0057 kg
o-Xylene	2.1E-08 lb	2.1E-08 kg
Oils, unspecified	2.4E-04 lb	2.4E-04 kg
p-Xylene	2.0E-09 lb	2.0E-09 kg
PAH, polycyclic aromatic hydrocarbons	6.6E-08 lb	6.6E-08 kg
Phenanthrene	9.3E-09 lb	9.3E-09 kg
Phenol	8.1E-05 lb	8.1E-05 kg
Phenol, 2,4-dimethyl-	1.5E-08 lb	1.5E-08 kg
Phosphate	2.8E-04 lb	2.8E-04 kg
Phosphorus, total	7.5E-05 lb	7.5E-05 kg
Propene	3.7E-08 lb	3.7E-08 kg
Propylene glycol	8.0E-04 lb	8.0E-04 kg
Pyrene	1.8E-09 lb	1.8E-09 kg
Selenium	8.1E-06 lb	8.1E-06 kg
Selenium compounds	1.8E-07 lb	1.8E-07 kg
Silicate	3.7E-04 lb	3.7E-04 kg
Silver	6.6E-11 lb	6.6E-11 kg
Silver compounds	5.5E-13 lb	5.5E-13 kg
Sodium	0.56 lb	0.56 kg
Sodium Bisulfate	8.0E-06 lb	8.0E-06 kg
Styrene	0.0080 lb	0.0080 kg
Sulfate	0.74 lb	0.74 kg
Sulfide	5.6E-06 lb	5.6E-06 kg
Sulfur	1.9E-09 lb	1.9E-09 kg
Suspended solids, unspecified	0.016 lb	0.016 kg
t-Butyl alcohol	6.6E-10 lb	6.6E-10 kg
t-Butyl methyl ether	5.5E-11 lb	5.5E-11 kg
TOC, Total Organic Carbon	0.078 lb	0.078 kg
Toluene	0.0080 lb	0.0080 kg
Zinc	3.6E-05 lb	3.6E-05 kg
Zinc compounds	2.7E-06 lb	2.7E-06 kg
Solid Wastes		
Hazardous waste to incineration	1.13 lb	1.13 kg
Hazardous waste to landfill	0.0025 lb	0.0025 kg
Solid waste process, to landfill	50.1 lb	50.1 kg
Solid Waste Sold for Recycling or Reuse	0.24 lb	0.24 kg
Solid waste, process to incineration	6.48 lb	6.48 kg
Solid waste, process to waste-to-energy incineration	488 lb	488 kg
Water Consumption*	648 gal	5,409 l

*Water consumption includes ground water, surface water, water from unspecified origin

Sources: Primary data, 2018

POLYETHER POLYOL FOR FLEXIBLE FOAM POLYURETHANES PRODUCTION

The manufacture of long-chain polyether polyol begins with the introduction of a potassium hydroxide catalyst to a polyol initiator, such as a triol. Sodium hydroxide data is used as a surrogate for potassium hydroxide data. This solution is reacted with propylene oxide and ethylene oxide to form an intermediate. Water is then added to this intermediate. A solvent is introduced, which absorbs the polyol from the water/catalyst. The density difference between the aqueous & organic phases is used to separate the two phases. Finally, the polyol is purified of solvent, side products and water through distillation (Franklin, 2019).

An individual weighted average for four leading polyether polyol producers (four plants) in the United States was calculated using the production amounts from each plant for polyether polyol. All companies provided data for the years 2015 or 2017. A weighted average was calculated from the data collected and used to develop the LCA model. The captured polyether polyol production amount is approximately 90 percent of the polyether polyol used for flexible foam polyurethane in the U.S. in 2015 (ACC, 2016). No coproducts are produced within polyether polyol manufacture.

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

Primary data were collected from polyether polyol manufacturers from the year 2015 (three plants) and 2017 (one plant). Companies providing data were given the option to collect data from 2015 or a year that would reflect more typical production conditions if 2015 was not typical. After reviewing individual company data in comparison to the average, each manufacturer verified data from 2015 or 2017 was a representative year for their company for polyether polyol production in North America.

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

Table 19 shows the averaged energy and emissions data for the production of 1,000 pounds and 1,000 kilograms of polyether polyol. In the case of some emissions, data was provided by fewer than the three producers. To indicate known emissions while protecting the confidentiality of individual company responses, some emissions are reported only by the order of magnitude of the average.

Table 19. LCI Data for the Production of Polyether Polyol for Flexible Foam Polyurethanes

	<u>1,000 lb</u>	<u>1,000 kg</u>	
Material Inputs			
Propylene Oxide	857 lb	857 kg	
Ethylene Oxide	107 lb	107 kg	
Glycerine	28.2 lb	28.2 kg	
Energy			
<i>Process Energy</i>			
Electricity from grid	12.3 kWh	27.1 kWh	
Electricity from cogen	26.4 kWh	58.1 kWh	
Natural gas	328 ft ³	20.5 m ³	
Fuel Gas**	55.7 ft ³	3.48 m ³	
<i>Transportation Energy</i>			
Truck			
Rail	1.62 ton·mi	5.20 tonne·km	
Pipeline -refinery products	50.2 ton·mi	162 tonne·km	
Truck	0.25 ton·mi	0.80 tonne·km	
Rail	1.08 ton·mi	3.48 tonne·km	
Environmental Emissions			
<i>Atmospheric Emissions</i>			
Particulates, unspecified	0.0010 lb	0.0010 kg	*
Particulates, < 2.5 um	0.0037 lb	0.0037 kg	
Particulates, > 2.5 um, and < 10um	0.010 lb	0.010 kg	*
Nitrogen oxides	0.013 lb	0.013 kg	
NMHC, non-methane hydrocarbons	0.0049 lb	0.0049 kg	
Hydrocarbons, unspecified	0.010 lb	0.010 kg	*
Sulfur oxides	8.5E-05 lb	8.5E-05 kg	
Carbon dioxide, fossil	21.0 lb	21.0 kg	
Methane	3.4E-04 lb	3.4E-04 kg	
Nitrous oxide	6.9E-05 lb	6.9E-05 kg	
Carbon monoxide	0.032 lb	0.032 kg	
Aldehydes, unspecified	1.0E-05 lb	1.0E-05 kg	*
Ammonia	1.0E-04 lb	1.0E-04 kg	*
Lead	1.0E-08 lb	1.0E-08 kg	*
Mercury	1.0E-08 lb	1.0E-08 kg	*
Chlorine	1.0E-05 lb	1.0E-05 kg	*
Propylene oxide	0.0010 lb	0.0010 kg	*
Ethylene oxide	1.0E-04 lb	1.0E-04 kg	*
Methane, chlorodifluoro-, HCFC-22	1.0E-05 lb	1.0E-05 kg	*
Organic substances, unspecified	1.0E-04 lb	1.0E-04 kg	*

Table 20. LCI Data for the Production of Polyether Polyol for Flexible Foam Polyurethanes (Continued)

	1,000 lb	1,000 kg	
<i>Waterborne Releases</i>			
Dissolved solids	0.0010 lb	0.0010 kg	*
BOD5, Biological Oxygen Demand	0.010 lb	0.010 kg	*
COD, Chemical Oxygen Demand	0.10 lb	0.10 kg	*
Suspended solids, unspecified	1.0E-04 lb	1.0E-04 kg	*
TOC, Total Organic Carbon	0.010 lb	0.010 kg	*
Hexane	0.10 lb	0.10 kg	*
Potassium	0.10 lb	0.10 kg	*
Solid Wastes			
Solid waste, process to landfill	3.10 lb	3.10 kg	
Solid Waste Sold for Recycling or Reuse	0.0079 lb	0.0079 kg	
Hazardous waste to WTE	0.48 lb	0.48 kg	
Water Consumption	166 gal	1,388 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.

** Fuel gas is created at other processes on site and combusted for energy for the polyether polyol process.

Source: Primary Data, 2022

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