CRADLE-TO-GATE LIFE CYCLE ANALYSIS OF POLYVINYL CHLORIDE (PVC) RESIN

Final Report

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Submitted by:

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PREFACE

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

This report was prepared for ACC by Franklin Associates, A Division of Eastern Research Group, Inc. as an independent contractor. This project was managed by Melissa Huff, Senior LCA Analyst and Project Manager. Anne Marie Molen assisted with data collection tasks, research, and report and appendix preparation. Mariya Absar aided with research and model review. Ben Young assisted with the oil and natural gas research and updates.

Franklin Associates gratefully acknowledges the significant contribution to this project by Mike Levy, Keith Christman, and Prapti Muhuri of ACC in leading this project. Also acknowledged are the following companies: Formosa Plastics Corporation, Occidental Chemical Corporation, and Shintech Inc. who graciously provided primary Life Cycle Inventory data for PVC resin production using the suspension technology. Their effort in collecting data has added considerably to the quality of this life cycle assessment report. Finally, thank you to the subset of ACC and Vinyl Institute members who thoroughly reviewed this report.

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

December, 2021

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LIST OF ACRONYMS

(Alphabetical)

ACC	AMERICAN CHEMISTRY COUNCIL
AP	ACIDIFICATION POTENTIAL
BOD	BIOCHEMICAL OXYGEN DEMAND
COD	CHEMICAL OXYGEN DEMAND
CFC	CHLOROFLUOROCARBON
EDC	ETHYLENE DICHLORIDE
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 TRANSPORTATION
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
PVC	POLYVINYL CHLORIDE
MJ	MEGAJOULE
MM	MILLION
NAPAP	NATIONAL ACID PRECIPITATION ASSESSMENT PROGRAM
NMVOC	NON-METHANE VOLATILE ORGANIC COMPOUNDS
NREL	NATIONAL RENEWABLE ENERGY LABORATORY

ODP	OZONE DEPLETION POTENTIAL
POCP	PHOTOCHEMICAL SMOG FORMATION (HISTORICALLY PHOTOCHEMICAL OXIDANT CREATION POTENTIAL)
PVC	POLYVINYL CHLORIDE
RCRA	RESOURCE CONSERVATION AND RECOVERY ACT
SI	INTERNATIONAL SYSTEM OF UNITS
TEQ	TOXICITY EQUIVALENTS
TRACI	TOOL FOR THE REDUCTION AND ASSESSMENT OF CHEMICAL AND OTHER ENVIRONMENTAL IMPACTS
TRI	TOXIC RELEASE INVENTORY
VI	VINYL INSTITUTE
VCM	VINYL CHLORIDE MONOMER

CRADLE-TO-GATE LIFE CYCLE ASSESSMENT OF POLYVINYL CHLORIDE (PVC) RESIN

INTRODUCTION

This study provides the American Chemical Council (ACC), their members, users of the U.S. LCI Database, and the public at large with information about the life cycle inventory and impacts for the production of polyvinyl chloride (PVC) resin, which is used in the production of a variety of applications such as siding, window frames, pipes, insulation and jacketing of wiring, and various car components[1] in North America. 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.

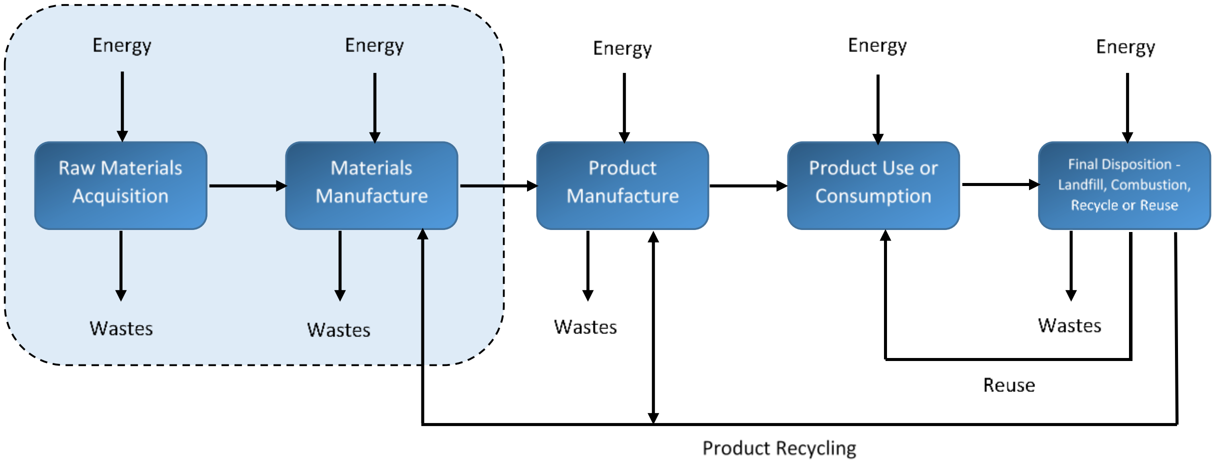

Figure 1. General materials flow for "cradle-to-grave" analysis of a product system. The dashed box indicates the boundaries of this analysis.

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.

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[1] Abbreviated list from https://www.vinylinfo.org/uses/ .

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 emissions, waterborne discharges, and solid waste resulting from the production of PVC resin. It is considered a cradle-to-gate boundary system because this analysis ends with the PVC resin production. The system boundaries stop at the PVC resin production so that the resin data can be linked to a fabrication process where it is an input material, and end-of-life data to create full life cycle inventories for a variety of products, such as piping systems, wire and cable insulation, and house siding. The method used for this inventory has been conducted following internationally accepted standards for LCI and LCA methodology as outlined in the International Organization for Standardization (ISO) 14040 and 14044 standard documents[2].

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 releases, and solid wastes) over the defined scope of the study. The LCI data for the PVC unit process is shown separately in the attached appendix. The LCI data for the olefins system is shown in the appendix of a separate report, ***Cradle-to-Gate Life Cycle Analysis of Olefins***[3]. All unit processes will be made available to the National Renewable Energy Laboratory (NREL) who maintains the U.S. LCI Database.

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

STUDY GOAL AND SCOPE

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

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

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

STUDY GOAL AND INTENDED USE

The purpose of this LCA is to document the LCI data and then evaluate the environmental profile of PVC resin. The intended use of the study results is twofold:

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

According to ISO 14040 and 14044 standards, a peer review is not required as no comparative assertions of competing materials or products are made in this study. This report has been internally reviewed, as well as reviewed by some members of ACC and the Vinyl Institute (VI).

This report is the property of ACC and may be used by the trade association or members or the general public at ACC's discretion.

FUNCTIONAL UNIT

The function of PVC resin is its forming into various products, for example, pipes for water delivery or electrical wire jacketing and insulation. As the study boundary concludes at the PVC resin, a mass functional unit has been chosen. Results for this analysis are shown on a basis of both 1,000 pounds and 1,000 kilograms of PVC 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 PVC resin manufacture:

- Raw material extraction (e.g., extraction of petroleum and natural gas as feedstocks) through ethylene dichloride/vinyl chloride monomer (EDC/VCM) production, and incoming transportation for each process, and
- PVC resin manufacture, including incoming transportation.

Because upstream olefin manufacture impacts the results for the production of PVC, some discussion about ethylene data and meta-data is included throughout this report. However, the LCI data for the olefins system is shown in the appendix of a separate report, *Cradle-to-Gate Life Cycle Analysis of Olefins*[4]*.* This report presents LCI results, as well as LCIA results, for PVC resin manufacture. Figure 2 presents the flow diagram for all unit processes included in the production of PVC resin. A unit process description and tables for each box shown in

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

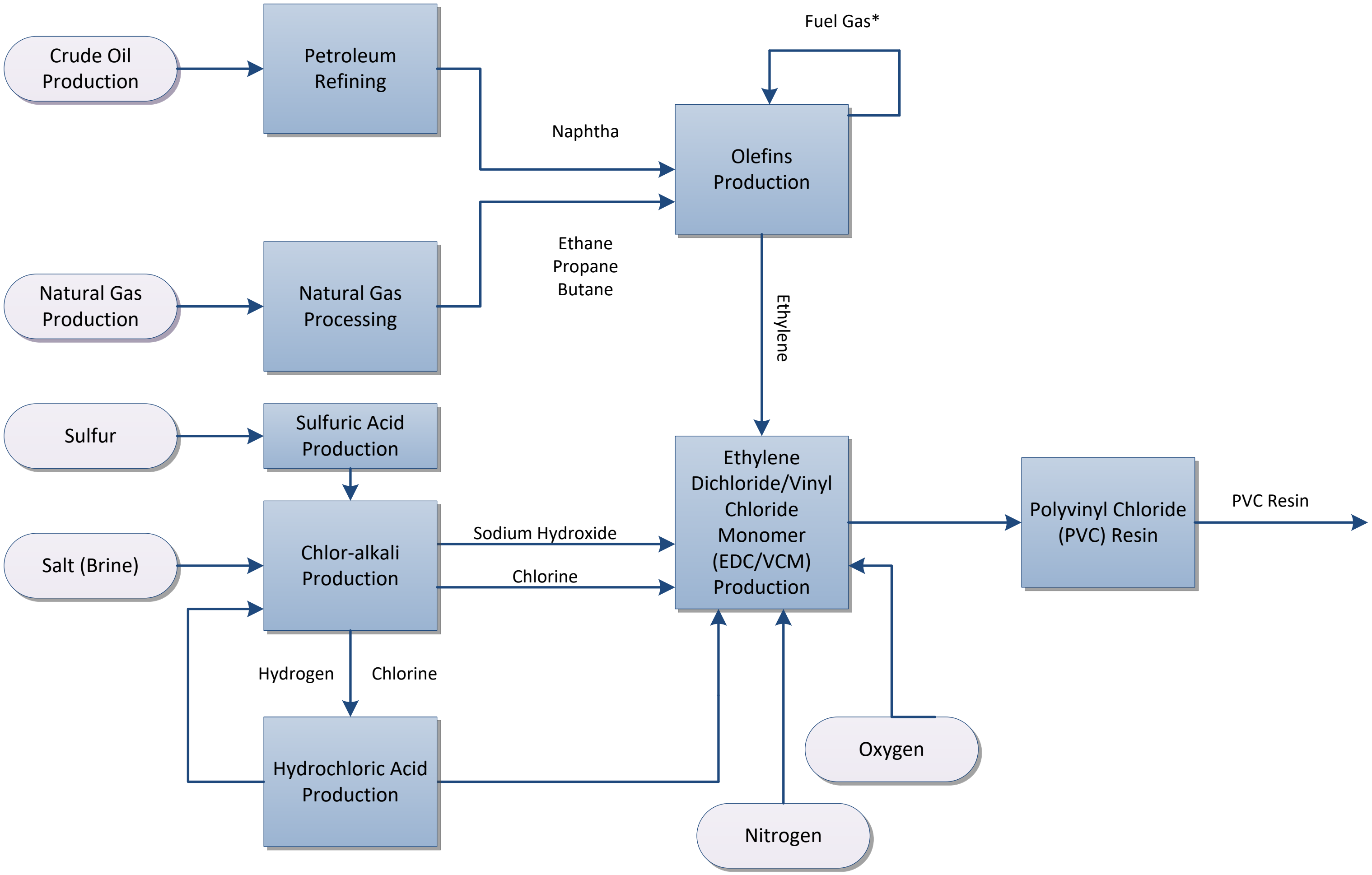

Figure 2. Flow diagram for the Production of Polyvinyl chloride (PVC) Resin.

Note: Data for salt (brine), hydrochloric acid (partial), oxygen and nitrogen use data from ecoinvent which are adapted to U.S. conditions. Nitrogen is an ancillary material input. Sulfuric acid is used during the drying process of chlorine and is only allocated to the chlorine production.
*Fuel gas used for energy is created from off-gas produced in the process.

the flow diagram can be found in the attached appendix or in the olefins report previously released.

Technological Scope

PVC resin is commonly produced in North America by two main technology types: suspension and dispersion (emulsion) polymerization of VCM. Other blending technologies may be used for specialty PVC. The data presented in this study represents the suspension polymerization of VCM, which is the primary technology used in North America to create PVC and is used by all three data providers in the U.S. Initiators, catalysts, and other polymerization chemistry additives are not included in this LCA.

The EDC collected data included its production through both direct chlorination and oxychlorination within each plant. The VCM production is exclusively created by thermal cracking within the U.S. All plants providing LCI data used these technologies.

Only the membrane cell technology was included for the chlor-alkali plants. All plants provided data for only this technology.

Temporal and Geographic Scope

For the PVC resin primary data, companies were requested to provide data for the year 2015, the most recent full year of PVC resin production prior to the project initiation date. Companies providing data were given the option to collect data from the year preceding or following 2015 if either year would reflect more typical production conditions. For the PVC resin and EDC/VCM data collected, each company provided data for the year 2015. For the Chlor-alkali data, 1 company provided data from 2015 and two from 2017. After reviewing individual company data in comparison to the average, each manufacturer verified their data was representative of an average year for PVC resin, EDC/VCM, and Chlor-alkali production at their company.

The geographic scope of the analysis is the manufacture of PVC resin in North America. All PVC resin data collected were from plants in the United States and modeled using North American databases such as the U.S. LCI database and Franklin Associates' private database, as well as ecoinvent for some chemicals. The U.S. electricity grid from 2016 was taken from information in Emissions & Generation Resource Integrated Database (eGRID) 2016 database.

Exclusions from the Scope

The following are not included in the study:

- **Miscellaneous materials and additives.** Selected materials such as catalysts, pigments, ancillary materials, or other additives which total less than one percent by weight of the net process inputs are typically not included in assessments. Omitting miscellaneous materials and additives keeps the scope of the study focused. It is possible that production of some substances used in small amounts may be energy and resource intensive or may release toxic emissions; however, the impacts would have to be very large in proportion to their mass in order to significantly affect overall results and conclusions. For this study, no use of resource-intensive or high-toxicity chemicals or additives was identified. Therefore, the results for the resin are not expected to be understated by any significant amount due to substances that may be used in small amounts.

- **Compounded additives beyond the PVC resin process.** PVC is commonly compounded with other additives to create certain physical properties for specific products. These compound additives are beyond the boundaries of the PVC resin production and so not included in this analysis.
- **Capital equipment, facilities, and infrastructure.** The energy and wastes associated with the manufacture of buildings, roads, pipelines, motor vehicles, industrial machinery, etc. are not included. The energy and emissions associated with production of capital equipment, facilities, and infrastructure generally become negligible when averaged over the total output of product or service provided over their useful lifetimes.
- **Space conditioning.** The fuels and power consumed to heat, cool, and light manufacturing establishments are omitted from the calculations when possible. For manufacturing plants that carry out thermal processing or otherwise consume large amounts of energy, space conditioning energy is quite low compared to process energy. The data collection forms developed for this project specifically requested that the data provider either exclude energy use for space conditioning or indicate if the reported energy requirements included space conditioning. Energy use for space conditioning, lighting, and other overhead activities is not expected to make a significant contribution to total energy use for the resin system.
- **Support personnel requirements**. The energy and wastes associated with research and development, sales, and administrative personnel or related activities have not been included in this study. Similar to space conditioning, energy requirements and related emissions are assumed to be quite small for support personnel activities.

INVENTORY AND IMPACT ASSESSMENT RESULTS CATEGORIES

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

The LCI and LCIA results categories and methods applied in this study are displayed in Table 1. This study addresses global, regional, and local impact categories. For most of the impact categories examined, the TRACI 2.1 method, developed by the United States Environmental

Protection Agency (EPA) specific to U.S. conditions and updated in 2012, is employed.[5] For the category of Global Warming Potential (GWP), contributing elementary flows are characterized using factors reported by the Intergovernmental Panel on Climate Change (IPCC) in 2013 with a 100 year time horizon.[6] In addition, the following LCI results are included in the results reported in the analysis:

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

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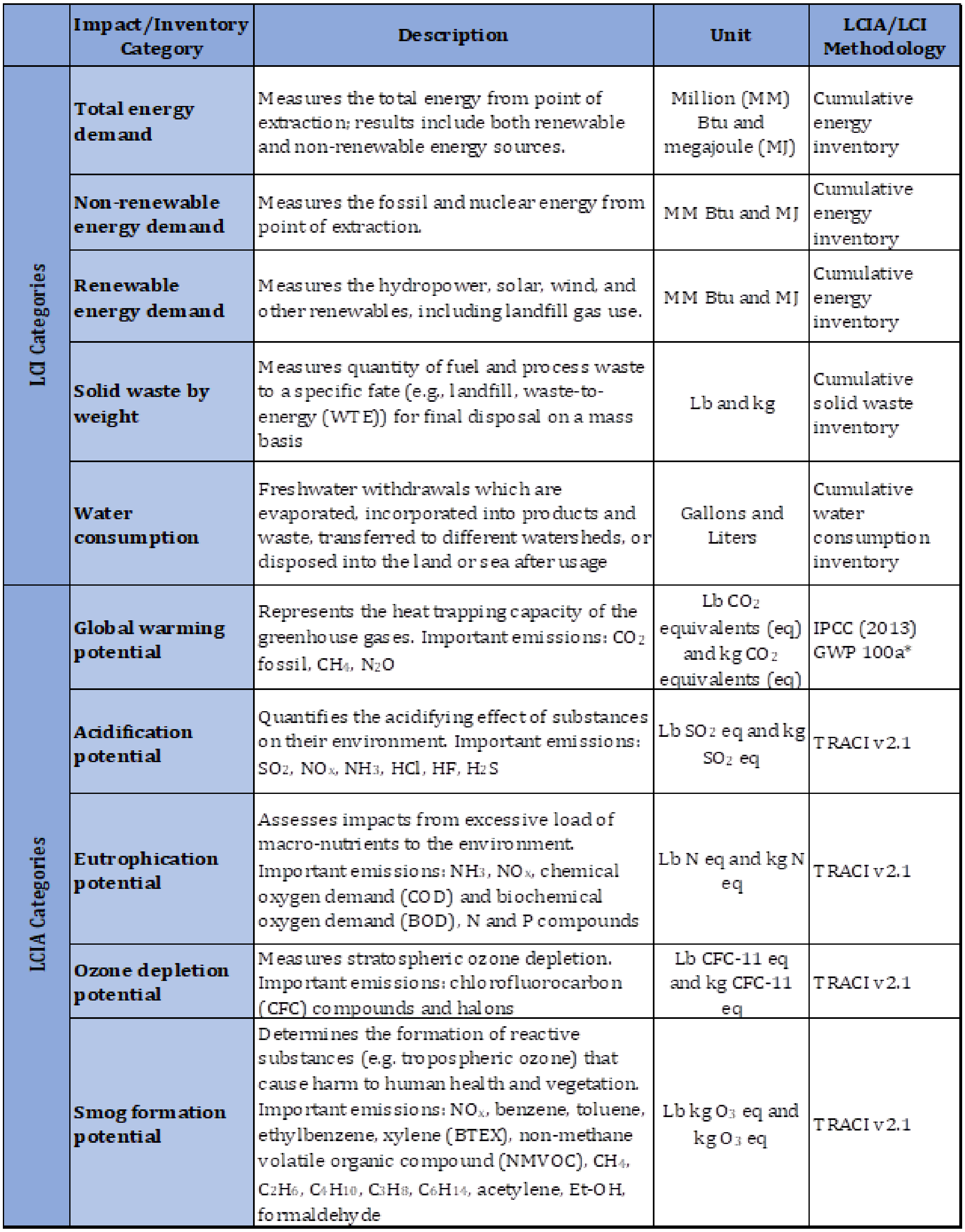
[5] Bare, J. C. Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Version 2.1 - User's Manual; EPA/600/R-12/554 2012.

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

Table 1. Summary of LCI/LCIA Impact Categories



	Impact/Inventory Category	Description	Unit	LCIA/LCI Methodology
LCI Categories	**Total energy demand**	Measures the total energy from point of extraction; results include both renewable and non-renewable energy sources.	Million (MM) Btu and megajoule (MJ)	Cumulative energy inventory
	Non-renewable energy demand	Measures the fossil and nuclear energy from point of extraction.	MM Btu and MJ	Cumulative energy inventory
	Renewable energy demand	Measures the hydropower, solar, wind, and other renewables, including landfill gas use.	MM Btu and MJ	Cumulative energy inventory
	Solid waste by weight	Measures quantity of fuel and process waste to a specific fate (e.g., landfill, waste-to-energy (WTE)) for final disposal on a mass basis	Lb and kg	Cumulative solid waste inventory
	Water consumption	Freshwater withdrawals which are evaporated, incorporated into products and waste, transferred to different watersheds, or disposed into the land or sea after usage	Gallons and Liters	Cumulative water consumption inventory
LCIA Categories	**Global warming potential**	Represents the heat trapping capacity of the greenhouse gases. Important emissions: CO_2 fossil, CH_4, N_2O	Lb CO_2 equivalents (eq) and kg CO_2 equivalents (eq)	IPCC (2013) GWP 100a*
	Acidification potential	Quantifies the acidifying effect of substances on their environment. Important emissions: SO_2, NO_x, NH_3, HCl, HF, H_2S	Lb SO_2 eq and kg SO_2 eq	TRACI v2.1
	Eutrophication potential	Assesses impacts from excessive load of macro-nutrients to the environment. Important emissions: NH_3, NO_x, chemical oxygen demand (COD) and biochemical oxygen demand (BOD), N and P compounds	Lb N eq and kg N eq	TRACI v2.1
	Ozone depletion potential	Measures stratospheric ozone depletion. Important emissions: chlorofluorocarbon (CFC) compounds and halons	Lb CFC-11 eq and kg CFC-11 eq	TRACI v2.1
	Smog formation potential	Determines the formation of reactive substances (e.g. tropospheric ozone) that cause harm to human health and vegetation. Important emissions: NO_x, benzene, toluene, ethylbenzene, xylene (BTEX), non-methane volatile organic compound (NMVOC), CH_4, C_2H_6, C_4H_{10}, C_3H_8, C_6H_{14}, acetylene, Et-OH, formaldehyde	Lb kg O_3 eq and kg O_3 eq	TRACI v2.1

DATA SOURCES

The purpose of this study is to develop a life cycle profile for PVC resin using the most recent data available for each process. A weighted average was calculated for the PVC resin primary data (production for the year 2015) collected for this analysis. A weighted average of primary data was also calculated for the EDC/VCM (production for the year 2015) and Chlor-alkali (production for the years 2015/2017) processes. The ethylene data was also calculated from an average of primary datasets for 2015. Secondary data was researched in 2017 for crude oil extraction and refining and natural gas production and processing. All included processes are shown in Figure 2.

Four PVC producers (six plants) provided data. Three PVC manufacturers (four plants) provided data for the production of PVC using suspension polymerization. One company (two plants) submitted data for production of PVC using a combination of technologies; suspension, dispersion and microdispersion. Because the overall average is significantly affected when including the combination of technologies to produce PVC, data from this company is excluded. All companies provided data for the year 2015. A weighted average was calculated from the data collected and used to develop the LCA model. The captured PVC resin production amount is approximately 54 percent[7] of the PVC resin production in the U.S. in 2015. Only small amounts of off-spec product are a coproduct of PVC resin production, and a mass basis was used to allocate burdens among the coproducts. Due to the reporting of certain emissions by less than 3 companies, industry average Toxic Release Inventory (TRI) data has been included for 6 emissions (see Table 21) to improve the data quality of the PVC resin.

Primary LCI data for EDC/VCM manufacture were collected from three producers (three plants). Each plant provided data for the year 2015. A weighted average was calculated from the data collected and used to develop the LCA model. Small amounts of heavy ends and excess hydrochloric acid are produced from this process and were given coproduct credit using mass allocation if sold outside the company. If the hydrochloric acid is recycled or used within the plant, no allocation was given. Due to the reporting of certain emissions by less than 3 companies, TRI data has been included for 6 emissions (see Table 20) to improve the data quality of the EDC/VCM.

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 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

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[7] Franklin Associates calculations using 2015 resin production amounts from The Resin Review, The Annual Statistical Report of the North American Plastics Industry by ACC. April, 2016.

as a fuel in the chlor-alkali or down-stream PVC processes or it was used to make hydrochloric acid on-site.

LCI data for the production of olefins including ethylene, were collected from three producers (ten plants) in North America – in the United States and Canada. All companies provided data for the year 2015. A weighted average was calculated from the data collected and used to develop the LCA model. Ethylene is a coproduct of olefin production, and a mass basis was used to allocate the environmental burdens among these coproducts.

The data for the remaining materials (natural gas, petroleum, sodium chloride, sulfur, sulfuric acid, hydrochloric acid, oxygen, and nitrogen) used to produce PVC resin are from secondary sources.

Process descriptions and LCI data for sodium chloride, sulfur, sulfuric acid, sodium hydroxide, chlorine, hydrogen, hydrochloric acid, EDC/VCM and PVC resin are provided in the Appendix at the end of this report. Other unit processes can be found in the separate report, *Cradle-to-Gate Life Cycle Analysis of Olefins.*

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

The remaining datasets were either updated using geographical and technologically relevant data from government or privately available statistics/studies within the US or drawn from either The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model or ecoinvent[8]. 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 salt (brine), hydrochloric acid, and nitrogen inputs for PVC resin are adapted from ecoinvent. 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

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[8] 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), PVC.1218–1230. Available at: <http://link.springer.com/10.1007/s11367-016-1087-8> [Accessed Sept, 2018].

representative available for the systems studied. Data sets were reviewed for completeness and material balances, and follow-up was conducted as needed to resolve any questions about the input and output flows, process technology, etc. The aggregated averaged datasets were also reviewed by the providing companies as compared to the provided dataset. Companies were requested to review whether their data were complete and to comment about their or the average dataset.

Representativeness: PVC resin manufactured in North America is produced using either gas-phase, solution, or slurry loop reactors. PVC resin producers from the United States provided data from their facilities using technology ranging from average to state-of-the-art. All of the PVC resin produced by the data providers come from the suspension technology. According to 2015 PVC resin production statistics in The Resin Review 2016[9], 54 percent of the PVC production in the US and Canada is accounted for in the data collected for this analysis.

Primary data were collected from olefin manufacturers from the year 2015 and 2016. Companies providing data were given the option to collect data from the year preceding or following 2015 if either year would reflect more typical production conditions. After reviewing individual company data in comparison to the average, each manufacturer verified data from 2015 or 2016 was a representative year for olefin 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 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 PVC resin unit process data was based on the best available data at the time the study was conducted. As in all LCA studies, the ability to develop a representative average is determined by the number of companies willing to participate. Data from this analysis was used to develop the most representative average for PVC resin production in 2015-2016 as was possible.

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

Order of Magnitude: In some cases, emissions data were reported by fewer than three companies. To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by order of magnitude. An order of magnitude of a number is the smallest power of 10 used to represent that number. For

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[9] The Resin Review 2016. American Chemistry Council. 2016

example, if the average of two data points for a particular emission is 2.5E-4, it would be shown as 1.0E-4 to ensure confidentiality of the data providers. 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 Chlor-alkali process, EDC/VCM, PVC resin and steam cracking of the olefins and hydrogen. 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 PVC resin and olefins.

Franklin Associates follows the guidelines for allocating the environmental burdens among the coproducts as shown in the ISO 14044:2006 standard on life cycle assessment requirements and guidelines[10]. In this standard, the preferred hierarchy for handling allocation is (1) avoid allocation where possible, (2) allocate flows based on direct physical relationships to product outputs, (3) use some other relationship between elementary flows and product output. No single allocation method is suitable for every scenario. As described in ISO 14044 section 4.3.4.2, when allocation cannot be avoided, the preferred partitioning approach should reflect the underlying physical relationships between the different products or functions.

Material Coproducts

Some processes lend themselves to physical allocation because they have physical parameters that provide a good representation of the environmental burdens of each co-product. Examples of various allocation methods are mass, stoichiometric, elemental, reaction enthalpy, and economic allocation. Simple mass and enthalpy allocation have been chosen as the common forms of allocation in this analysis. However, these allocation methods were not chosen as a default choice but made on a case by case basis after due consideration of the chemistry and basis for production.

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

Material coproducts were created in all the intermediate chemical process steps collected for this analysis, as well as the primary PVC resin production. The material coproducts from ethylene production for all plants included ethylene, pyrolysis gasoline, butadiene, ethane, hydrogen, acetylene, crude benzene, and small amounts of various heavy end products. The EDC/VCM process creates a heavy ends product from distillation and in some plants a small amount of excess hydrochloric acid as material coproducts given mass allocation. Most of the hydrochloric acid created in EDC/VCM production is used on-site in the process, so no coproduct allocation is given for that amount. The material coproducts from PVC resin production include off-spec product.

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

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

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

Energy Coproducts Exported from System Boundaries

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

Chlor-Alkali Plant Allocations

The allocations for the Chlor-Alkali plant follow the allocations given in the Euro Chlor report, *An Eco-profile and Environmental Product Declaration of the European Chlor-Alkali Industry*[11]. These allocations were followed due to the likelihood that comparisons will be made between the North American and European LCAs by companies and LCA practitioners in both continents. This will ensure that the differences in datasets will not be caused by differing allocation methods. The original North American Chlor-alkali LCI data used mass allocation on all inputs and outputs.

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[11] An Eco-profile and Environmental Product Declaration of the European Chlor-Alkali Industry. Chlorine (The chlor-alkali process) Euro Chlor. September, 2013.

As avoiding allocation of coproducts is not possible since chlorine, sodium hydroxide, and hydrogen are all produced from the process, allocations have been made to focus on which product the inputs or outputs associate within the process. The following allocations are made to the Chlor-Alkali LCI data:

- The sodium chloride input was given stoichiometric allocation among the three products. As the plants providing data produced for sale only chlorine, sodium hydroxide and hydrogen, the sodium chloride input was split between the chlorine and sodium hydroxide using the stoichiometry of the chemical reaction.
- The sulfuric acid input was used specifically to dry the chlorine and so has fully been allocated to the chlorine product.
- All chlorine-based air emissions or waterborne wastes are allocated to the chlorine product.
- All sodium hydroxide emissions are allocated to the sodium hydroxide product.
- All hydrogen emissions are allocated to the hydrogen product.
- All other inputs or outputs of the chlor-alkali process are allocated by mass to all three products.

TRI Emissions Use for EDC/VCM and PVC Resin

Some emissions data collected for the EDC/VCM and PVC resin were replaced by industry average TRI emissions data. This was due to one or more of the data providers having incomplete emissions data during the LCI submission, so that the emission was either excluded or on an order of magnitude with lower data quality. The emissions using industry average TRI data include vinyl chloride, EDC, carbon tetrachloride, methyl chloroform, 1,1,1 trichloroethane, and dioxins (calculated as Toxic Equivalent Values). VI provided insight on the assumptions needed to calculate these values on an industry average basis for only PVC using suspension technology. The bullets below provide the assumptions used per VI.

- Production amounts for U.S. PVC produced from suspension technology was provided.
- Identification of sites that produce PVC from suspension technology.
- Identification of which sites include both EDC/VCM plants and PVC plants.
- Estimated percentages for each emission produced on-site by the EDC/VCM versus PVC plant.
- Toxic Equivalent Values (TEQ) is used for dioxins.

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 EDC/VCM and PVC plants in the United States; five plants in Texas and two plants in Louisiana. . The U.S. average fuel consumption by electrical utilities was used for the electricity within this analysis. This electricity data set uses the Emissions & Generation Resource Integrated Database (eGRID) 2016 database [12]. Table 2 provides a breakdown of energy sources and the contribution by percentage of each source to the grid mix.

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%.

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.

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

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

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:** All data providers for this study reported natural gas as the fuel used for cogeneration. According to 2016 industry statistics, natural gas accounted for 75 percent of industrial cogeneration, while coal and biomass accounted for the largest portion of the remaining fuels used[13].

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

   The 50 percent conversion efficiency was an estimate after reviewing EIA fuel consumption and electricity net generation data from cogeneration plants in 2016.[14] 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

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

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

enthalpy tables (in most cases steam ranged from 1,000 to 1,200 Btu/lb). An efficiency of 80 percent was used for the industrial boiler to calculate the amount of fuel used. This Btu value was then divided by the Btu value of fuel consumed in the cogeneration boiler to determine the steam allocation factor. The 80 percent efficiency used is common for a conventional natural gas boiler, which should not change when considering the steam portion of the cogeneration system. Pounds of steam, temperature and pressure were provided by participating plants. Steam tables were used to calculate energy amounts, which was divided by the efficiency and converted to natural gas amounts in cubic feet.

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 PVC:

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 PVC:

- Cradle-to-incoming materials – includes the raw materials through the production of EDC/VCM
- PVC resin production – is the gate-to-gate PVC resin unit process and includes the production of fuels used within the plant.

Tables and figures are provided for PVC 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-EDC/VCM and EDC/VCM system are interchangeable). The phrase “gate-to-gate” is defined as including only the onsite process/fuels and no upstream or downstream material inputs and emissions.

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 makes up almost 40 percent of the PVC resin inputs.

The average total energy required to produce PVC is 24.8 million Btu per 1,000 pounds of PVC resin or 57.8 gigajoule (GJ) per 1,000 kilograms of PVC resin. Table 3 shows total energy demand for the life cycle of PVC resin production. The PVC resin production energy has been split out from the energy required for incoming materials, which includes the vinyl chloride monomer and all inputs to it (see Figure 2). A little less than 9 percent of the total energy is required to produce the PVC resin alone. The remaining 91 percent is used to create the incoming materials from cradle-to-VCM.

Table 3. Total Energy Demand for PVC Resin

	Basis: 1,000 pounds		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	MM Btu	***MM Btu***	***MM Btu***
Cradle-to-Incoming Materials	22.6	22.5	0.17
Virgin PVC Resin Production	2.20	2.15	0.051
Virgin PVC Resin Production	**24.8**	**24.6**	**0.22**
	Basis: 1,000 kilograms		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	GJ	***GJ***	***GJ***
Cradle-to-Incoming Materials	52.6	52.2	0.40
Virgin PVC Resin Production	5.11	4.99	0.12
Total	**57.8**	**57.2**	**0.52**
	Percentage		
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**
	%	***%***	***%***
Cradle-to-Incoming Materials	91.1%	90.5%	0.7%
Virgin PVC Resin Production	8.9%	8.6%	0.2%
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 cradle-to-PVC resin total energy, 99.1 percent 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 (0.12 GJ/1000 kg) used at the PVC resin plant comes solely from hydropower and other renewable sources (geothermal, solar, etc.) used for electricity production. If regional electricity grids were used, it is possible that specific types of renewable energy sources would change (e.g., less hydropower, more wind), but the change in energy amount from renewable sources would be small.

The energy representing natural gas and petroleum used as raw material inputs for the production of ethylene used to produce the ethylene dichloride in the manufacture of PVC resin are included in the cradle-to-incoming material amounts in Table 3. The energy inherent in these raw materials are called material feedstock energy. Of the 57.8 GJ of energy for 1,000 kg of PVC resin, 24.5 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 PVC resin. Approximately 42 percent of the total energy is inherent energy in the natural gas and petroleum used as a feedstock to create ethylene, which in turn is used as an input to EDC, which is used to create PVC resin. Ninety percent of the feedstock sources for ethylene come from natural gas, while 10 percent of the feedstock sources come from oil. For this analysis an average ethylene dataset was used to model the production of EDC used for PVC manufacture. Because EDC producers typically source ethylene from their own olefins plants that use 100 percent natural gas liquids to produce ethylene, the total energy shown in Table 3 may be minorly overstated.

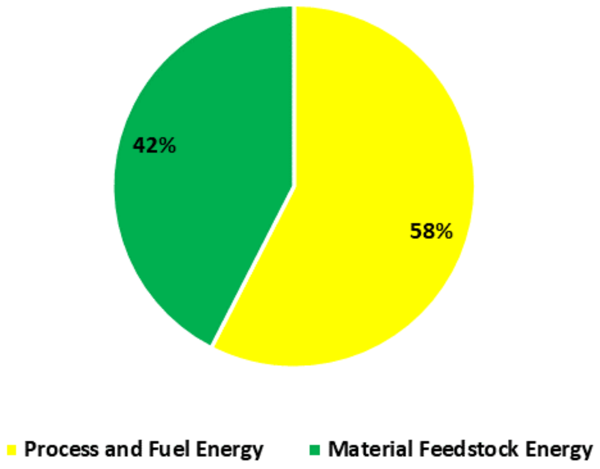

Figure 3. Process/Fuel and Material Feedstock Percentages for PVC Resin

Energy Demand by Fuel Type

The total energy demand by fuel type for PVC 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 ethylene, which accounts for 40 percent of the main material input into PVC resin. These material feedstock fuels are part of the energy shown in the natural gas and petroleum split out in the following table and figure. The gate-to-gate production energy for PVC resin in the following table and figure represents the energy required for transportation of raw materials to PVC manufacturers, the energy required to produce the PVC, and the production of the fuels needed to manufacture the PVC resin.

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 the ethylene production.

Of the results for PVC resin production shown in Table 4 and Figure 4, 85 percent of the energy used (49.3 GJ/57.8 GJ) is from natural gas. At the PVC resin plant, nearly 72 percent of the energy used (3.7 GJ/5.11 GJ) comes from natural gas. Of that natural gas used at the PVC resin plant, approximately one-third is required to create electricity off-site, while two-thirds is combusted on-site. Petroleum comprises approximately 5 percent (2.93 GJ/57.8 GJ) of the fuel used for the PVC resin production system; 2.3 GJ of the 2.93 GJ is material resource energy. Two-thirds of the petroleum for the PVC plant is used during transport of the incoming materials.

The coal use shown is combusted for electricity use. Over 20 percent of the energy created using coal is used by the PVC resin plant. The Chlor-alkali process that creates the chlorine necessary to produce the vinyl chloride monomer uses mainly electricity and accounts for more than 40 percent of the coal use. The 2016 U.S. electricity grid is used for this study. In this grid, approximately 30 percent of the electricity production in the US uses coal as a fuel source, while a third of the grid comes from natural gas and 20 percent from uranium. The hydropower, nuclear, and other energy are all used to create electricity, with the exception of a small amount of landfill gas used in the ethylene production shown within other renewables.

Table 4. Energy Demand by Fuel Type for PVC Resin

	Basis: 1,000 pounds						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	MM Btu	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*	*MM Btu*
Cradle-to-Incoming Materials	22.6	19.6	1.21	0.99	0.67	0.071	0.10
Virgin PVC Resin Production	2.20	1.59	0.054	0.30	0.20	0.021	0.030
Total	**24.8**	**21.2**	**1.26**	**1.29**	**0.87**	**0.092**	**0.13**
	Basis: 1,000 kilograms						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	GJ	*GJ*	*GJ*	*GJ*	*GJ*	*GJ*	*GJ*
Cradle-to-Incoming Materials	52.6	45.6	2.81	2.31	1.55	0.16	0.23
Virgin PVC Resin Production	5.11	3.70	0.12	0.70	0.47	0.050	0.070
Total	**57.8**	**49.3**	**2.93**	**3.00**	**2.02**	**0.21**	**0.30**
	Percentage of Total						
	Total Energy	**Natural Gas**	**Petroleum**	**Coal**	**Nuclear**	**Hydropower**	**Other Renewable**
	%	*%*	*%*	*%*	*%*	*%*	*%*
Cradle-to-Incoming Materials	91.1%	79%	4.9%	4.0%	2.7%	0.28%	0.41%
Virgin PVC Resin Production	8.9%	6.4%	0.2%	1.2%	0.8%	0.09%	0.12%
Total	**100%**	**85%**	**5.1%**	**5.2%**	**3.5%**	**0.37%**	**0.53%**

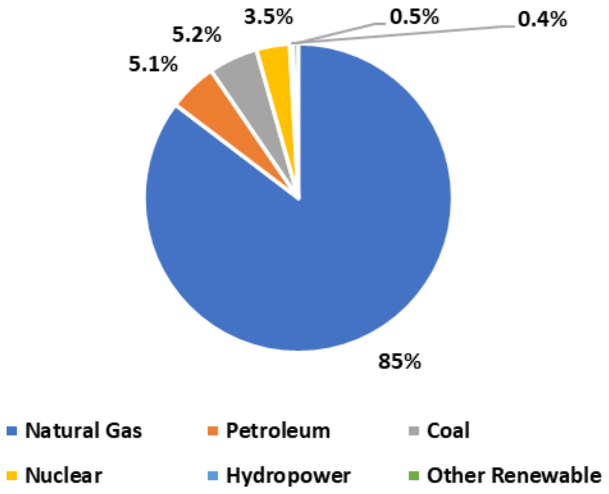

Figure 4. Percentage of Energy Separated by Fuel Type for PVC Resin

SOLID WASTE

Solid waste results include the following types of wastes:

- **Process wastes** that are generated by the various processes from raw material acquisition through production of the olefins (e.g., sludges and residues from chemical reactions and material processing steps)
- **Fuel-related wastes** from the production and combustion of fuels used for process energy and transportation energy (e.g., refinery wastes, coal combustion ash)

No postconsumer wastes of the PVC resin are included in this analysis as no product is made from the material in the analysis boundaries.

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

Results for solid waste by weight for the PVC resin system are shown in Table 5 and Figure 5. The solid wastes have been separated into hazardous and non-hazardous waste categories, as well as by the cradle-to-incoming materials and the PVC plant. As shown in Figure 5, only 17 percent of the total solid waste is created during the PVC resin unit process. This comes from fuels combusted or as a process solid waste during the PVC production. More than 80 percent of solid waste connected with the PVC unit process comes from coal production and combustion used to create electricity for the PVC resin plant. Less than one percent of the solid wastes associated with the PVC unit process are process wastes at the PVC resin plant.

The majority of solid waste, 83 percent, comes from the production of incoming materials used to produce PVC resin. Again, more than half of the solid waste created by the incoming processes are coming from the coal production and combustion used to create electricity used at each manufacturing plant. The EDC/VCM & ethylene plants produce almost 7 percent of the solid waste generated from incoming materials. Approximately 30 percent of these solid wastes come from the extraction of oil and gas required for both the material use and fuel use at the plants and at electricity production.

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. Of the total solid wastes, less than 1 percent are considered hazardous wastes. Of that percentage, a little more than one percent of the total hazardous solid waste amount comes from the PVC plant. The greatest portion, more than 85 percent, comes from the ethylene plant, while most of the remaining is from the EDC/VCM plant.

Table 5 also provides a breakout of the total solid wastes by the disposal fate. Of the hazardous waste, more than 91 percent is incinerated without energy capture. Focusing specifically on the non-hazardous solid waste produced, 96 percent of the non-hazardous solid waste is landfilled, while 4 percent is incinerated, and a minute amount (0.0003%) is sent to waste-to-energy. Solid wastes were also sent for recycling/recovery in many of the plants where data was collected but were not included in Table 5.

Table 5. Total Solid Wastes for PVC Resin

	Basis: 1,000 pounds								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	lb	lb	lb	lb	lb	lb	lb	lb	lb
Cradle-to-Incoming Materials	69.9	0	0.71	0.066	0.77	3.0E-04	2.95	66.2	69.2
Virgin PVC Resin Production	14.3	0	0.014	0	0.014	0	0	14.3	14.3
Total	**84.3**	**0**	**0.72**	**0.066**	**0.79**	**3.0E-04**	**2.95**	**80.5**	**83.5**
	Basis: 1,000 kilograms								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	kg	kg	kg	kg	kg	kg	kg	kg	kg
Cradle-to-Incoming Materials	69.9	0	0.71	0.066	0.77	3.0E-04	2.95	66.2	69.2
Virgin PVC Resin Production	14.3	0	0.014	0	0.014	0	0	14.3	14.3
Total	**84.3**	**0**	**0.72**	**0.066**	**0.79**	**3.0E-04**	**2.95**	**80.5**	**83.5**
	Percentage of Total								
		Hazardous Wastes				Non-Hazardous Wastes			
	Total Solid Waste	Waste-to-Energy	Incineration	Landfill	Hazardous Waste Total	Waste-to-Energy	Incineration	Landfill	Non-Hazardous Waste Total
	%	%	%	%	%	%	%	%	%
Cradle-to-Incoming Materials	83%	0%	0.84%	0.08%	0.92%	0.0%	3.5%	79%	82%
Virgin PVC Resin Production	17%	0%	0.02%	0%	0.02%	0%	0%	17%	17%
Total	**100%**	**0%**	**0.86%**	**0.08%**	**0.9%**	**0.0%**	**3.5%**	**95.6%**	**99.1%**

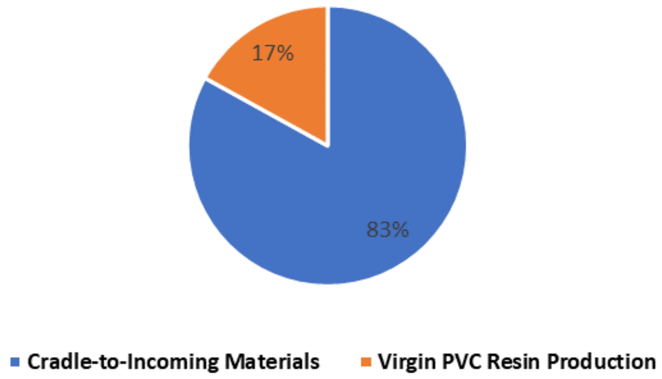

Figure 5. Percentage of Total Solid Wastes for PVC Resin System

WATER CONSUMPTION

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

Water consumption results for PVC resin production are shown in Table 6 and Figure 6. The majority of consumption of water within the PVC resin is comes from the cradle-to-incoming materials (71 percent). The majority of the water consumption comes from the individual unit processes and not the fuel production. When looking at the individual unit processes, about 23 percent of the total is consumed at the PVC plant. The primary water consumption data for the PVC resin does include two of three PVC manufacturers that release water to a different watershed than the initial water source, which is considered consumption in the methodology used. Sodium chloride (as a brine) contributes almost 17 percent of the water consumption. This is secondary data used from a European source. The ethylene primary dataset contributes 12 percent and EDC/VCM contributes 10 percent of the water consumption amount. These primary datasets also include some plants that release water to a different watershed. 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 23 percent of the total water consumption. The remaining water consumption comes from the other unit processes and the extraction of natural gas.

Table 6. Water Consumption for PVC Resin

	Total Water Consumption		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	Gallons	***Liters***	***%***
Cradle-to-Incoming Materials	1,214	10,131	71%
Virgin PVC Resin Production	498	4,160	29%
Total	**1,713**	**14,290**	**100%**

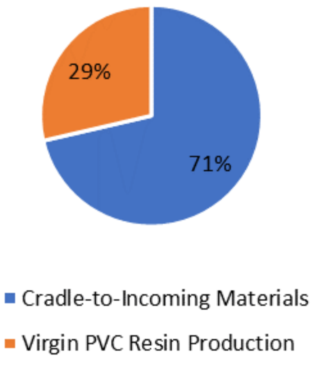

Figure 6. Water Consumption for PVC Resin

GLOBAL WARMING POTENTIAL

The primary atmospheric emissions reported in this analysis that contribute over 99 percent of the total global warming potential for each system are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. Other contributors include some chloroform, methyl chloride and hydrochlorofluorocarbons (HCFCs), but these contribute much less than 1 percent of the total shown. The greenhouse gas (GHG) emissions that make up the majority of the global warming potential amount are mainly from the combustion of fuels. In the primary data collected, combustion emissions from flare have been included as process emissions and so their totals may be overstated by small amounts due to the inclusion of combustion of fuel used during the flare. Data providers were asked to estimate percentages of greenhouse gases from flare from that of the combustion of fuels. Any non-fossil carbon dioxide emissions, such as those from the burning of wood-derived fuel, is a return of carbon dioxide to the atmosphere in the same form as it was originally removed from the atmosphere during the biomass growth cycle; therefore, any carbon dioxide emissions from combustion or decomposition of biomass-derived products are not considered a net contributor to global warming.

The 100-year global warming potential (GWP) factors for each of these main GHG emissions as reported in the Intergovernmental Panel on Climate Change (IPCC) 2013[15] are: fossil carbon dioxide 1, fossil methane 28, and nitrous oxide 265. The GWP factor for a substance represents the relative global warming contribution of a pound of that substance compared to a pound of carbon dioxide. The weights of each greenhouse gas are multiplied by its GWP factor to arrive at the total GWP results. Although normally GWP results are closely related to the energy results, the feedstock energy is not associated with GWP due to the sequestration of the feedstock material within the plastic. It is the potential energy associated with the feedstock material, which is not combusted to create greenhouse gases.

Table 7 and Figure 7 show life cycle GWP results for the PVC resin system. Of the total, 85 percent of the GWP are attributed to emissions from the incoming cradle-to-EDC/VCM materials, with the remaining associated with the production of the PVC resin. The largest amount of the GWP is created by the combustion of natural gas within the industrial boilers at the plants, which makes up 41 percent of the total GWP. The combustion of coal and natural gas in boilers to create electricity comprises 22 percent of the total GWP. The production of ethylene, which accounts for 16 percent of the total GWP, comes directly from the release of greenhouse gases at the olefins plant. The natural gas extraction, processing, and transport used as a material input to the olefins plant comprises 14 percent of the total GWP. The process greenhouse gases released at the PVC resin plants are much less than 1 percent of the total, with the remainder of the GWP associated with the PVC resin production coming from the electricity production offsite and natural gas boilers onsite.

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[15] 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 PVC Resin

	Global Warming Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb CO2 eq	***kg CO2 eq***	***%***
Cradle-to-Incoming Materials	1,781	1,781	85%
Virgin PVC Resin Production	314	314	15%
Total	**2,095**	**2,095**	**100%**

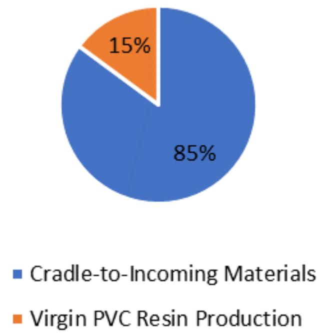

Figure 7. Global Warming Potential for PVC Resin

ACIDIFICATION POTENTIAL

Acidification assesses the potential of emissions to contribute to the formation and deposit of acid rain on soil and water, which can cause serious harm to plant and animal life as well as damage to infrastructure. Acidification potential modeling in TRACI incorporates the results of an atmospheric chemistry and transport model, developed by the U.S. National Acid Precipitation Assessment Program (NAPAP), to estimate total North American terrestrial deposition due to atmospheric emissions of NO_x and SO_2, as a function of the emissions location.[16,17]

Acidification impacts are typically dominated by fossil fuel combustion emissions, particularly sulfur dioxide (SO_2) and nitrogen oxides (NO_x). Emissions from combustion of fossil fuels, especially coal, to generate grid electricity is a significant contributor to

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[16] 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.

[17] 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.

acidification impacts for the system. Also, emissions from the extraction and processing of natural gas impact the AP category.

Table 8 shows total acidification potential (AP) results for the PVC resin system. Results are shown graphically in Figure 8. In the AP category, 16 percent of the AP coming from PVC resin production and about 84 percent comes from the raw and intermediate material unit processes. Forty-one percent of the AP amount comes from the extraction and processing of natural gas for materials and fuels, which is used to create 90 percent of the material inputs to the ethylene plants. Another 41 percent, comes from the combustion of coal for electricity. The combustion of natural gas in both industrial (onsite) and utility (offsite) boilers contributes 8 percent of the AP results. Emissions from the ethylene and EDC/VCM plants make up almost 4 percent of the AP results. Much less than 1 percent of the total AP comes directly from the PVC resin production. The largest percent of the 16 percent shown as from PVC resin production in Table 8 comes from the production of electricity.

Table 8. Acidification Potential for PVC Resin

	Acidification Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb SO2 eq	*kg SO2 eq*	*%*
Cradle-to-Incoming Materials	5.14	5.14	84%
Virgin PVC Resin Production	1.00	1.00	16%
Total	**6.14**	**6.14**	**100%**

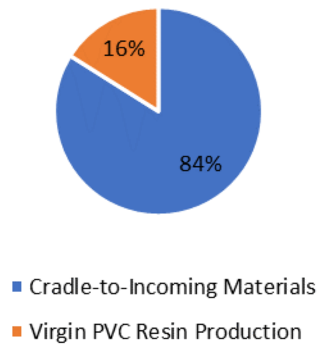

Figure 8. Acidification Potential for PVC Resin

EUTROPHICATION POTENTIAL

Eutrophication occurs when excess nutrients (nitrates, phosphates) are introduced to surface water causing the rapid growth of aquatic plants. Excess releases of these substances may provide undesired effects on the waterways.[18] The TRACI characterization factors for eutrophication are the product of a nutrient factor and a transport factor.[19] The nutrient factor is based on the amount of plant growth caused by each emission discharge, while the transport factor accounts for the probability that the discharge will reach a body of water. Atmospheric emissions of nitrogen oxides (NO_x) as well as waterborne emissions of nitrogen, phosphorus, ammonia, biochemical oxygen demand (BOD), and chemical oxygen demand (COD) are the main contributors to eutrophication impacts.

Eutrophication potential (EP) results for PVC resin are shown in Table 9 and illustrated in Figure 9. The largest portion, over 86 percent, of the EP results come from the raw and intermediate materials used to create PVC resin. The extraction of natural gas for materials and fuels releases over 50 percent of the emissions related to the EP impact. Approximately 17 percent of the EP impact is released from coal and natural gas combustion during electricity production, while natural gas combusted in boilers onsite at the plants create 8 percent of the EP results. The ethylene plant process emissions comprise 6 percent of the EP impact results. The PVC resin production generates 14 percent of the EP impact, with over 5 percent representing the combustion of fuels for electricity. Less than 2 percent of the total EP impact comes from process emissions released at the PVC plant.

Table 9. Eutrophication Potential for PVC Resin

	Eutrophication Potential		
	Basis: 1,000 Pounds	**Basis: 1,000 kilograms**	**Percentage of Total**
	lb N eq	***kg N eq***	***%***
Cradle-to-Incoming Materials	0.22	0.22	86%
Virgin PVC Resin Production	0.036	0.036	14%
Total	**0.26**	**0.26**	**100%**

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

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

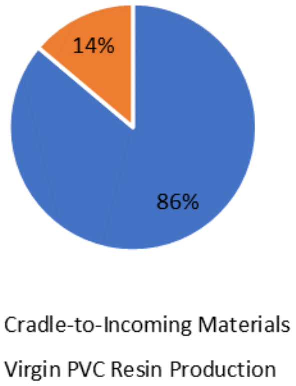

Figure 9. Eutrophication Potential for PVC Resin

OZONE DEPLETION POTENTIAL

Stratospheric ozone depletion (ODP) is the reduction of the protective ozone within the stratosphere caused by emissions of ozone-depleting substance (e.g., CFCs and halons). The ozone depletion impact category characterizes the potential to destroy ozone based on a chemical's reactivity and lifetime. Effects related to ozone depletion can include skin cancer, cataracts, material damage, immune system suppression, crop damage, and other plant and animal effects. For the PVC resin system, almost 90 percent of the ODP is released during the EDC/VCM process, while much of the remaining 10 percent is released at the PVC resin plant. The remaining minute amount of the ODP shown is from the extraction of petroleum used for the production of petroleum-based fuels.

Table 10 shows total ODP results for the PVC resin system, which are also shown graphically in Figure 10. Ozone depletion results for the PVC resin system are dominated by the carbon tetrachloride release at the EDC/VCM plant, contributing 82 percent of the total ozone depletion impacts. The methyl chloride released at both the PVC and EDC/VCM plants contributes almost 18 percent of the total ODP. Both of these emissions have been estimated from the TRI database using assumptions to allocate them to the EDC/VCM and PVC resin processes as discussed in the methods section. The remaining emissions contributing to ODP are minute amounts of a few CFCs, HCFCs, and halons that are emitted during the extraction of petroleum, which is used as fuel and material in the production of ethylene, as well as the production of petroleum-based fuels.

Table 10. Ozone Depletion Potential for PVC Resin

	Ozone Depletion Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb CFC-11 eq	*kg CFC-11 eq*	*%*
Cradle-to-Incoming Materials	0.0022	0.0022	89.5%
Virgin PVC Resin Production	2.6E-04	2.6E-04	10.5%
Total	**0.0025**	**0.0025**	**100%**

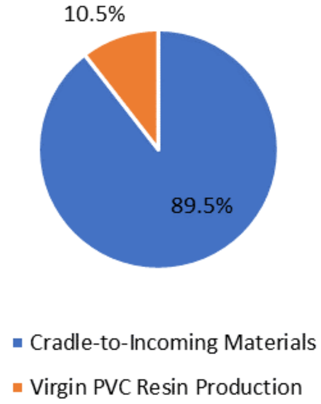

Figure 10. Ozone Depletion Potential for PVC Resin

PHOTOCHEMICAL SMOG FORMATION

The photochemical smog formation (historically photochemical oxidant creation potential) (POCP) impact category characterizes the potential of airborne emissions to cause photochemical smog. The creation of photochemical smog occurs when sunlight reacts with NO_x and volatile organic compounds (VOCs), resulting in tropospheric (ground-level) ozone and particulate matter. Endpoints of such smog creation can include increased human mortality, asthma, and deleterious effects on plant growth.[20] Smog formation impact are generally dominated by emissions associated with fuel combustion, so that impacts are higher for life cycle stages and components that have higher process fuel and transportation fuel requirements. In this case, NO_x makes up more than 97 percent of the smog formation emissions, with VOCs consisting of another 2 percent. Natural gas extraction is where the largest amounts of these emissions are released, making up over 50 percent of the total results of the POCP category.

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

Smog formation potential results for PVC resin are displayed in Table 11 and illustrated in Figure 11. Approximately 87% of the POCP impact results comes from the raw and intermediate materials (cradle-to-incoming materials). The ethylene and EDC/VCM plants together release almost 7 percent of the total emissions resulting the POCP. Approximately two-thirds of the remainder of the POCP impact results within the cradle-to-incoming materials amount are from the production and combustion of natural gas for both materials and fuels. Over 10 percent of the POCP results also are created from the combustion of coal.

The remaining 13 percent of the POCP impact results is released from the PVC resin unit process. Of that percentage, over 45 percent of the POCP from the PVC resin plant comes from the use of electricity in the plant, which includes the combustion of natural gas and coal at power plants and cogeneration plants. Approximately 30 percent of the POCP impact results are released at the PVC resin plant as natural gas combustion emissions. The remaining percentage in the PVC resin production comes from transport of incoming materials.

Table 11. Photochemical Smog Formation Potential for PVC Resin

	Photochemical Smog Potential		
	Basis: 1,000 Pounds	Basis: 1,000 kilograms	Percentage of Total
	lb O3 eq	*kg O3 eq*	*%*
Cradle-to-Incoming Materials	113	113	87%
Virgin PVC Resin Production	17.4	17.4	13%
Total	**131**	**131**	**100%**

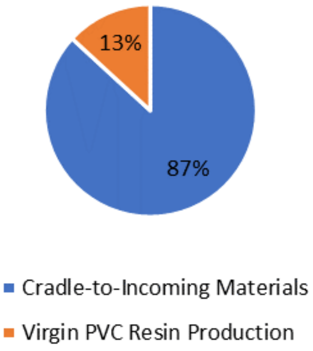

Figure 11. Photochemical Smog Formation Potential for PVC Resin

COMPARISON OF 2021 AND 2013 LCI AND LCIA PVC RESULTS

This section provides a comparison of life cycle inventory and impact assessment category results that were included in an update[21] to the original virgin PVC resin system[22] 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 2013 and 2021 PVC resin results in both English and SI units and includes the percent difference for each category. Percent difference between systems, discussed further below, is defined as the difference between energy totals divided by the average of the two system totals. The results in Table 12 show an increase in the energy category, with a decrease in the solid waste and global warming potential. Note that in some cases, the change is small enough not to be considered significantly different. Comparisons of these results have been analyzed in this section focusing on the main differences causing the change in each category. It should be noted that all figures in this section provide a percent increase or decrease above the comparable bars, which is calculated as the difference between the totals divided by the 2013 value.

Based on the uncertainties in LCI energy data, energy differences between systems are not considered meaningful unless the percent difference between system results is greater than 10 percent. The threshold guidelines are not intended to be interpreted as rigorous statistical uncertainty analysis, but rather are provided as general guidelines for readers to use when interpreting differences in system results, to ensure that undue importance is not placed on small differences that fall within the uncertainties of the underlying data. The solid waste and GWP, which includes factors used to weight and convert the GHG emissions released to an impact category, require a minimum 25 percent difference to consider results significantly different.

Broadly, results differences between the two averaged datasets are predominantly due to the use of different companies and manufacturing plants when updating the ethylene, Chlor-alkali, EDC/VCM, and PVC primary data. Each plant producing the same resin or chemical varies by the amounts of input materials used, fuel types and amounts used, amounts of emissions released, etc. The amalgamation of these changes lead to differences affecting the results. In the updated data, PVC resin, EDC/VCM, and ethylene are representative of the year 2015, while the Chlor-alkali data represents the years 2015 (2 plants) and 2017 (1 plant). For ethylene, EDC/VCM and PVC, some of the same plants provided data; however, some of the plants in the current average were not included in the original data collection which took place between 2004 and 2006. The number of companies participating in this

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[21] American Chemistry Council, Plastics Division, Cradle-to-Resin Life Cycle Inventory of Polyvinyl Chloride (PVC). Prepared by Franklin Associates, A Division of ERG. December, 2013.

[22] 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.

update for the EDC/VCM and PVC resin remained at 3; however, two plants that participated in collecting data for the original analysis provided data for 2015. In chlor-alkali, one plant used was in the original data collection by its previous owner. The other two current data providers replaced data from chlor-alkali plants who had provided data in the 1990s.

Table 12. Comparison of 2013 and 2021 LCI and LCIA Results for Virgin PVC Resin

	1000 pounds of Virgin Polyvinyl Chloride Resin				
	LCI Results				***LCIA Results***
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**	**Total Solid Waste***	**Global Warming**
	MM Btu	***MM Btu***	***MM Btu***	***lb***	***lb CO_2 eq***
PVC 2021	24.8	24.6	0.22	83.5	2,095
PVC 2013	23.7	23.7	0.10	140	2,262
	1000 kilograms of Virgin Polyvinyl Chloride Resin				
	LCI Results				***LCIA Results***
	Total Energy	**Non-Renewable Energy**	**Renewable Energy**	**Total Solid Waste***	**Global Warming**
	GJ	***GJ***	***GJ***	***kg***	***kg CO_2 eq***
PVC 2021	57.8	57.2	0.52	83.5	2,095
PVC 2013	55.1	54.8	0.22	140	2,262
Percent Difference	5%	4%	79%	-51%	-8%

*Total Solid Waste excludes hazardous solid waste for 2021 as this category was not included as Solid Waste in 2013.

ENERGY COMPARISON

Overall, the total energy for PVC resin system shows an increase of 2.7 GJ on a 1,000 kg basis (1.1 MMBtu/1,000 lb). This is a 5 percent difference in total energy as compared to the original results. This percentage is small and would not be considered significantly different due to differences in the plants, as well as an increase of the average raw material amounts to the EDC/VCM plant. When comparing the PVC resin unit process average energy data, data from the plants showed that some energy sources had increased by small amounts while others decreased by similar amounts. The differences in PVC energy overall decreased by 15 percent, which would be considered significantly different from the previous average. Figure 12 provides a graphical perspective of the unit processes associated with the total energy decrease from the original energy amounts.

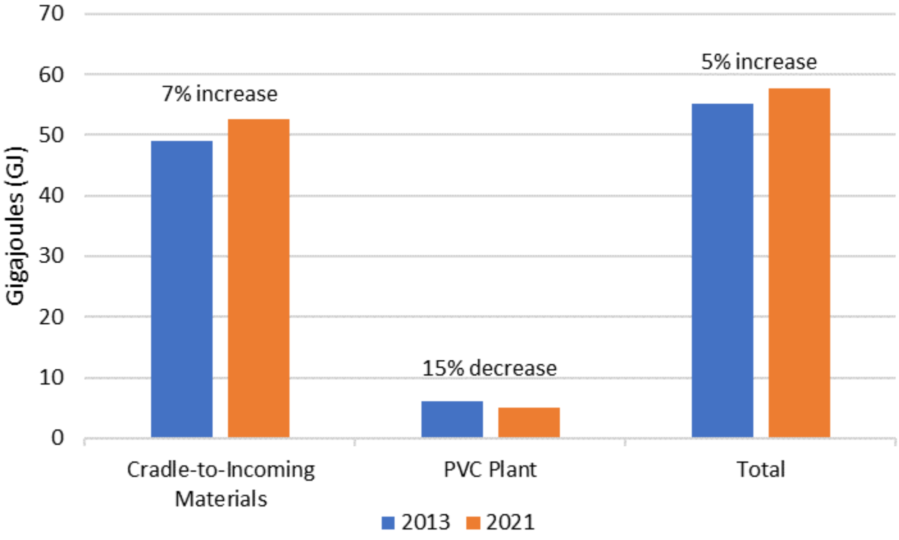

Figure 12. Change in Energy by Stage per 1,000 kg (GJ)

The energy of material resource, which pertains to the amount of inherent energy from the raw materials increased by a small amount for PVC resin update due to an increased amount of ethylene input to the EDC/VCM process compared, as well as small differences in the heating values used for oil and gas. This increase in energy of material resource accounts for half of the increased amount of total energy. The energy for converting vinyl chloride monomer to PVC resin decreased by 15 percent compared to the 2004-2006 energy for this process. Some of this decrease may be due to efficiency improvements; however, the change may also be due to the fact that one of the plants in the current analysis was not in the original analysis. The current average energy usage is very similar to the previous average energy usage, even with one different plant participating, which suggests that the data provide a good representation of average North American production.

The difference in renewable energy increased more than 100 percent from the 2013 results. Although this seems large compared to the non-renewable energy, the renewable energy makes up less than one percent of the total energy even with the increase. 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. This increase in renewable energy is also seen when considering only the PVC plant, which uses electricity from the grid.

SOLID WASTE COMPARISON

When compared to the 2013 PVC resin total solid waste amount, the current PVC resin study shows over 56 kg per 1000 kg PVC resin less solid waste, which is a 51 percent difference and is considered a lower amount from the 2013 update. Decreases in solid waste occurred in most of the unit processes required to make PVC resin. Figure 13 provides a visual of the total solid waste amount split out by the PVC unit process and cradle-to-incoming materials. A decrease occurs for both cradle-to-incoming materials and at the PVC plant. Comparing the current process solid waste at the PVC plant to the 2013 solid waste, a 19 percent decrease is seen. The largest part of the decrease in solid waste at the PVC plant comes from the fuel use. This is possibly due to the decrease in coal use in the electricity grid used in 2016 as compared to the previous grid used. The decrease in cradle-to-incoming materials is due to lower amounts of process solid waste within the chlor-alkali, ethylene, and EDC/VCM plants, as well as being due to an overall decrease in the electricity use and decrease of coal use within the average electricity grid. Process solid wastes from the natural gas and crude oil production also decreased by small amounts.

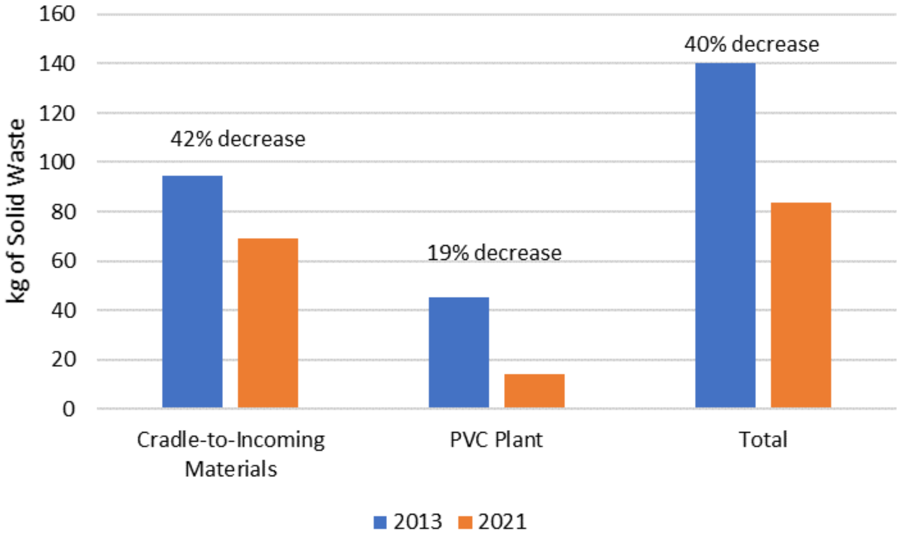

Figure 13. Decrease in Solid Waste Weight by Unit Process (kg Per 1,000 kg)

GLOBAL WARMING POTENTIAL COMPARISON

The global warming potential decreased by 167 kg CO_2 equivalents/1000 kg PVC resin, which calculates to an 8 percent difference. This percent difference is lower than the 25 percent limit and is not considered sizable enough to signify a definite difference in results. Figure 14 displays a column chart with the PVC resin and cradle-to-incoming materials results that makeup the decrease when comparing the 2013 and 2021 GWP results. Normally the global warming potential change is similar to the energy change, but in this case, the GWP has decreased while the energy increased a small amount. However, as stated in the energy comparison, half of the energy increase is allocated as energy of material resource. The total energy amount includes the material resource energy, which has no greenhouse gases associated with it as it is not combusted. If only the process/transport energy are compared for the original and updated PVC resin system, the percent increase in energy is closer to 3 percent. This small increase would be due to the increased raw material amounts in EDC/VCM, while the decrease in GWP for each of those raw materials would offset the energy increase, which leads to the GWP decrease.

The GWP specific to the PVC resin plant decreases by 20 percent, while the energy for the average PVC plant also decreased by a similar percentage. The decrease in GWP for the incoming materials comes in part from decreases in energy use for the raw materials and for the ethylene plant. Also, the previous chlor-alkali average included an amount of coal and distillate oil used in boilers within one of the older plants; whereas in the current average, these fuels are not used and instead hydrogen created from the chlor-alkali plant is used as fuel alongside natural gas. The amount of coal combusted for the US average electricity grid has decreased over time with an increase in natural gas combustion. Coal production and combustion releases higher amounts of greenhouse gases compared to natural gas production and combustion.

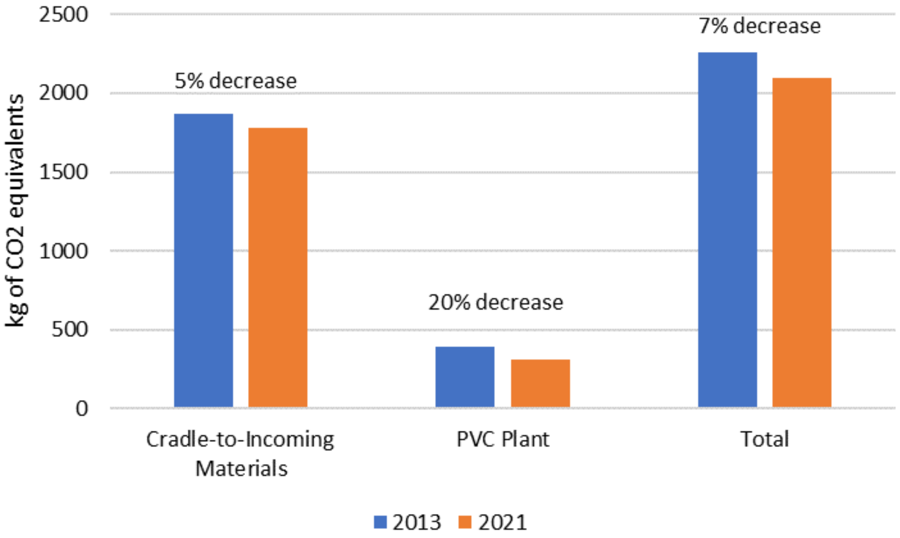

Figure 14. Decrease in Global Warming Potential by Unit Process (kg of CO2 eq. per 1,000 kg)

APPENDIX: POLYVINYL CHLORIDE (PVC) MANUFACTURE

This appendix discusses the manufacture of PVC, which is used for a variety of applications, such as siding, window frames, pipes, insulation and jacketing of wiring, and various car components. The captured PVC production amount is approximately 54 percent of the PVC production in the U.S. in 2015 (ACC, 2016). The flow diagram of processes included for PVC resin is provided in Figure 15.

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

- Sodium Chloride (Salt) Solution Mining
- Sulfur Production
- Sulfuric Acid Production
- Chlor-alkali Using the Membrane Cell (Chlorine, Sodium Hydroxide, Hydrogen)
- Hydrochloric Acid Production
- Ethylene Dichloride (EDC)/Vinyl Chloride Monomer (VCM) Production
- PVC Resin

LCI data for ethylene, chlor-alkali (chlorine, sodium hydroxide, and hydrogen), EDC/VCM and PVC resin production were collected for this update to the U.S. LCI plastics database by both member and non-member companies of the American Chemistry Council. Secondary data was used for crude oil extraction and refining and natural gas production and processing, salt mining, sulfur production, sulfuric acid production, oxygen production, nitrogen production, and hydrochloric acid production. LCI data for the production of ethylene, oil, and natural gas can be found in the report, ***Cradle-to-Gate Life Cycle Analysis of Olefins***.[23] LCI data for salt (brine), hydrochloric acid, oxygen, and nitrogen were adapted from the ecoinvent 3 database. The adaptations included the use of the US electricity grid and US transportation.

SODIUM CHLORIDE (SALT) SOLUTION MINING

Salt (sodium chloride) is an abundant, inexpensive commodity used mostly by the chlor-alkali and other chemical industries. The various technologies used include underground mining of rock salt, solution mining of salt brine, vacuum pan salt, and solar salt. Approximately 95 percent of salt-based chlorine and caustic facilities use brine salt (Bolen, 2016). Rock salt, vacuum pan salt and solar salt represent 5 percent of U.S. production and are thus not included in this data module. This data module represents solution mining techniques.

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

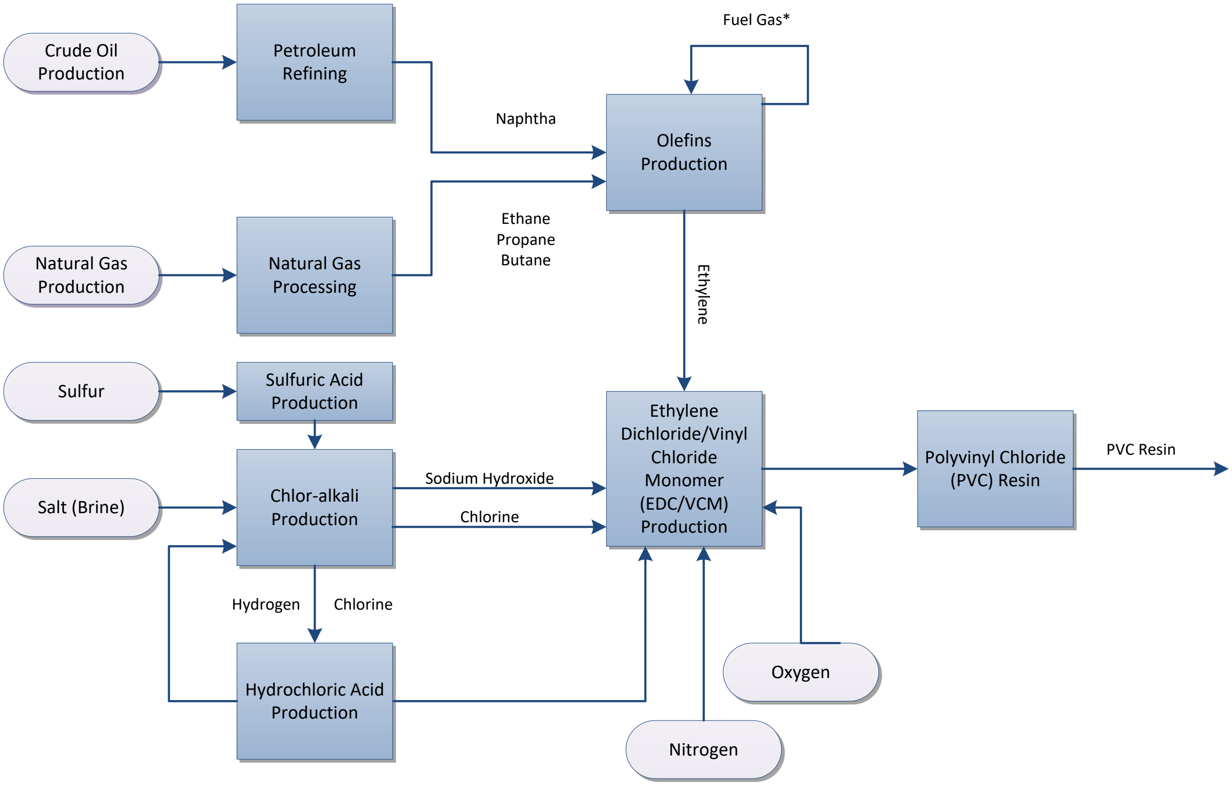

Figure 15. Flow diagram for the Production of Polyvinyl chloride (PVC) Resin.

Note: Data for salt (brine), hydrochloric acid (partial), oxygen and nitrogen use data from ecoinvent which are adapted to U.S. conditions. Nitrogen is an ancillary material input. Sulfuric acid is used during the drying process of chlorine and is only allocated to the chlorine production.

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

In solution mining, pressurized fresh water is pumped into the bedded salt underground through an injection well. The water mixes with the salt in the caves to produce the brine. The brine is then pumped to the surface for treatment. Brine for use in the chlor-alkali industry requires treatment to produce a specific purity and saturation for their process (TX Brine Co, 2019).

Table 13 provides the LCI data used for the solution mining of 1,000 pounds and 1,000 kilograms of salt (brine). This data provides the energy requirements of the solution mining of salt brine using ecoinvent data (Althaus, 2007a) adapted for the U.S. This adaptation included the conversion of heavy fuel oil use to natural gas using the heating values of the fuels. Also, the average U.S. electricity grid was used for the stated electricity. No air or water emissions data are available from salt solution mining. Since the solution mining involves no chemical reactions and minimal processing requirements, it is assumed that negligible process air emissions result. No data are available for other water effluents. However, EPA's Best Practicable control Technology currently available (BPT) limitations for sodium chloride production by solution mining stipulate that no process wastewater is returned to navigable waters. Any solution remaining after the recovery of salt brine can be returned to the body of water or salt deposit from which it originally came (DOE, 2000). Solution mining is a technology that does not generate significant amounts of solid wastes. It is thus assumed that solution mining for salt produces negligible quantities of solid waste.

Table 13. LCI Data for the Solution Mining of Salt (Brine)

	1,000 lb	1,000 kg
Inputs from Nature		
Sodium Chloride	1000 lb	1000 kg
Water	458 gallons	3,820 liters
Energy		
Process Energy		
Electricity from grid	30.4 kWh	67.0 kWh
Natural gas	155 ft^3	9.66 m^3

Note: Data was adapted from ecoinvent data. The energy created by the fuel heavy oil in the original data was converted to natural gas use for North America.

Source: Althaus (2007a) and Franklin (2021b).

SULFUR PRODUCTION

Sulfur exists in nature as elemental sulfur and is also found in ores such as pyrite (FeS2). Sulfur is also recovered from hydrogen sulfide (H2S), a component of petroleum and natural gas. The U.S. produces 93 percent of its elemental sulfur is recovered using the Claus process from natural gas and petroleum (Apodaca, 2016). The remaining is recovered as a byproduct from metal roasters and smelters. Only the Claus process is included in this analysis and is discussed here. In 2015, approximately 89 percent of the sulfur produced via Claus recovery is obtained from hydrogen sulfide recovered from petroleum refining, and the remaining 11 percent is recovered from natural gas sweetening (Apodaca, 2016).

Hydrogen sulfide is recovered from refinery gases by absorption in a solvent or by regenerative chemical absorption (Kent, 2007). Hydrogen sulfide concentrations in the gas from the absorption unit vary. For this analysis, an industry average H_2S gas concentration of 85 percent out of the absorption unit is used (Franklin, 1991 and Kent, 2007). This concentrated hydrogen sulfide stream is treated by the Claus process to recover the sulfur. The Claus process is based upon the reaction of hydrogen sulfide with sulfur dioxide according to the exothermic reaction (Kent, 2007):

$$2H_2S + SO_2 \rightarrow 3S + 2H_2O \qquad \text{(Reaction 1)}$$

Sulfur dioxide for the reaction is prepared by oxidation of hydrogen sulfide with air or oxygen in a furnace normally using the partial combustion process (straight-through process), the split-flow process or direct oxidation. The first two processes use a flame reaction furnace prior to the catalytic stages. The partial combustion method is used when the H_2S concentration is greater than 50 percent and the hydrocarbon concentration is less than 2 percent. The split stream process is used when there is an H_2S concentration of 15 to 50 percent and a hydrocarbon concentration of less than 5 percent. Direction oxidation reacts oxygen directly with the H_2S in the first catalytic reactor, producing the SO_2 required. This process is used less often than the partial combustion and split-flow and is more commonly used when the H_2S concentration is below 15 percent in the acid gas. (Linde, 2019)

In the partial combustion method, the hydrogen sulfide-rich gas stream is burned with a fuel gas in an oxygen-limited environment to oxidize one-third of the H_2S to SO_2 according to the reaction (Gary, 2001):

$$2H_2S + 2O_2 \rightarrow SO_2 + S + 2H_2O \qquad \text{(Reaction 2)}$$

The initial reaction can convert more than half of the incoming H_2S to elemental sulfur, which is removed from the burner (Linde, 2019). The H_2S/SO_2 mixture moves to the catalytic converter chambers.

In the split stream process, one-third of the hydrogen sulfide is split off and completely oxidized to SO_2 according to the reaction:

$$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O \quad \text{(Reaction 3)}$$

The remaining two-thirds of the H_2S is mixed with the combustion product and enters the catalytic converter chambers. There is enough H_2S burned to create the 2:1 ratio of H_2S to SO_2 in the catalyst beds. (Linde, 2019)

The H_2S and SO_2 mixture from either process is passed through one or more catalyst beds and is converted to sulfur, which is removed by condensers between each bed. For this analysis, an H_2S concentration of 85 percent has been assumed; therefore, it is also assumed that the partial combustion process is used.

Although efficiencies of 96 to 99 percent sulfur recovery have been demonstrated for the Claus process, recovery is usually not over 96 percent and is limited by thermodynamic considerations (Gary, 2001). For this analysis, a sulfur recovery efficiency of 95 percent is assumed.

The energy generated from burning hydrogen sulfide to produce SO_2 is usually recovered and used directly to reheat the process stream in secondary and tertiary condensers or recovered as steam for use in other processes (Gary, 2001). Heat released from cooling the exothermic reaction to form sulfur is also recovered.

The LCI data used for the production of 1,000 lb and 1,000 kg of sulfur by the Claus technology is given in Table 14.

Table 14. LCI Data for the Recovery of Sulfur by the Claus Technology

	1,000 lb		1,000 kg	
Inputs from Nature				
Natural gas	139	lb	139	kg
Crude oil	1,126	lb	1,126	kg
Energy				
Process Energy				
Electricity from grid	49.7	kWh	110	kWh
Natural gas	1,151	ft^3	71.9	m^3
Recovered energy	2.87	MM Btu	6.00	GJ
Environmental Emissions				
Atmospheric Emissions				
Aldehydes, unspecified	0.089	lb	0.089	kg
Carbon dioxide, fossil	210	lb	210	kg
Waterborne Releases				
Suspended solids, unspecified	0.0060	lb	0.0060	kg

Source: Apodaca (2016), Gary (2001), Franklin (1991)

SULFURIC ACID PRODUCTION

Over 90 percent of sulfuric acid produced in the U.S. is produced by the contact process (Zumdahl, 2017). The sulfur input streams used by contact plants can be of four different forms: (1) elemental sulfur, (2) spent sulfuric acid, (3) hydrogen sulfides, and (4) metal sulfide ores or smelter gas.

There are three basic steps in the contact process. The first step oxidizes (burns) sulfur to sulfur dioxide (SO_2). The gases, containing approximately 10 percent SO_2, from the burner are passed through a waste heat recovery boiler, which is used to generate steam, and where the gases are cooled (Ashar, 2013) The steam is usually used in adjacent processing plants and supplies energy to the sulfuric acid plant. The exported steam is given a credit and shown as avoided energy.

The second step catalytically oxidizes sulfur dioxide to sulfur trioxide (SO_3). Currently, a Vanadium catalyst is commonly used. This catalyst has not been included as an input. The third step dissolves the sulfur trioxide with the appropriate amount of water to at least a 98 percent solution of sulfuric acid. The efficiency of the absorption can be affected by the sulfuric acid concentration, temperature of the liquid and gas, moisture content in the raw gas, and the acid mist filter. (Ashar, 2013)

Process data for the production of 1,000 lb and 1,000 kg of sulfuric acid are shown in Table 15.

Table 15. LCI Data for the Production of Sulfur Acid

	1,000 lb		1,000 kg	
Material Inputs				
Sulfur	332	lb	332	kg
Inputs from Nature				
Oxygen	489	lb	489	kg
Water	184	lb	184	kg
Energy				
Process Energy				
Electricity from grid	19.3	kWh	42.5	kWh
Avoided Energy (1)				
Natural gas avoided due to export of vent gas	218	ft^3	13.6	m^3
Transportation Energy				
Truck	21.4	ton·mi	69.0	tonne·km
Rail	390	ton·mi	1,255	tonne·km
Ocean freighter	26.4	ton·mi	85.0	tonne·km
Environmental Emissions				
Atmospheric Emissions				
Sulfur dioxide	1.75	lb	1.75	kg
Sulfur trioxide	0.067	lb	0.067	kg
Waterborne Releases				
BOD5, Biological Oxygen Demand	0.30	lb	0.30	kg
Suspended solids, unspecified	0.10	lb	0.10	kg
Sulfuric acid	0.10	lb	0.10	kg
Solid Wastes				
Solid waste, process to landfill	0.015	lb	0.015	kg
Water Consumption	312	gal	2600	l

(1) Avoided energy is heat is produced during the process. This has been included as natural gas using system expansion.

(2) Transportation represents percentages using the Minerals yearbook for Sulfur. 43% coming from TX, 52% coming by rail from Canada and other states, and 5% coming by freighter from Mexico and EU. Assumption that the process is in Houston area for transport.

Sources: European Commission (2007), Franklin (2021a), Primary data (2002), Apodaca (2016)

CHLOR-ALKLAI USING THE MEMBRANE CELL (CHLORINE, SODIUM HYDROXIDE, HYDROGEN)

Sodium hydroxide, chlorine, and hydrogen are produced from salt by an electrolytic process. Overall, the aqueous sodium chloride solution is electrolyzed to produce sodium hydroxide, chlorine, and hydrogen gas.

For PVC production in North America, there are two main commercial processes for the electrolysis of sodium chloride: the diaphragm cell process and the membrane cell process. Membrane cell electrolysis is the most recent of these technologies and is increasingly gaining commercial acceptance to the point of becoming the most common chlor-alkali production method in North America. Membrane cell electrolysis has relatively low energy requirements and all new or updated facilities likely use this process (Chlorine Institute, 2014).

In the membrane cell process, pure brine is sent to the electrolyzer, which includes an anode and cathode separated by an ion exchange membrane. Chlorine gas is formed by oxidation at the anode. Sodium ions and water transfer across the membrane to the cathode compartment. In this area, the water is reduced to hydrogen gas and hydroxide ions. The hydroxide ions combine with the sodium ions to create sodium hydroxide at the cathode. The sodium hydroxide is created at approximately 32% solution, but evaporators can be used to concentrate the sodium hydroxide to a 50% solution. (Chlorine Institute, 2014)

The allocation to the three products in the chlor-alkali process are discussed in Chlor-Alkali Plant Allocations in the Coproduct Allocation section of the report. 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. As an overview, the sodium chloride and water were given stoichiometric allocation, while most of the remaining inputs and outputs use mass allocation. A few inputs/outputs were specific to the production of one coproduct and so allocated to that coproduct.

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. 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. One company requested to provide LCI data from 2017 as a typical year for chlor-alkali production at their plant. A weighted average was calculated from the data collected and used to develop the LCA model.

The chlor-alkali producers that provided data considered the technology at their facility from average to state-of-the-art. All data represent membrane cell electrolysis only.
Data providers reviewed their data as well as the average LCI data and provided questions on comments on the average, which Franklin Associates reviewed and responded until all companies understood and accepted the average dataset.

The energy requirements and environmental emissions for the production of 1,000 lb and 1000 kg of chlorine, sodium hydroxide and hydrogen are provided respectively in Table 16, Table 17, and Table 18. In the case of some emissions, data was provided by fewer than the 3 producers. To indicate known emissions while protecting the confidentiality of individual company responses, some emissions are reported only by the order of magnitude of the average.

HYDROCHLORIC ACID (HCL) PRODUCTION

Although there are a number of processes used to produce hydrochloric acid, however, the most predominant is produced as a byproduct from the chlorination of hydrocarbons. Most hydrochloric acid used in the production of ethylene dichloride comes from producing vinyl chloride monomer or from a nearby chlor-alkali plant. This analysis uses the synthesis of the elements hydrogen and chloride ($H_2 + Cl_2 \rightarrow 2HCl$) at the chlor-alkali plant. The acid is produced by burning hydrogen in the chlorine tail gas, which creates a mainly pure acid and requires no further treatment (Kent, 2007). The HCl is commonly absorbed in water to create the solution, which can range from 20 to 50 percent commonly.

The energy and chlorine emission data used in this analysis for hydrochloric acid comes from the ecoinvent database (Althaus, 2007b). The electricity amount was adapted to the U.S. average electricity grid within the models. The hydrochloric acid emission is an order of magnitude from the HCl emission provided by less than 3 of the chlor-alkali plants. It is shown in Table 19.

Table 16. LCI Data for the Production of Chlorine Using the Membrane Cell Technology

	1,000 lb		1,000 kg		
Material Inputs					
Sodium chloride, brine solution	1,035	lb	1,035	kg	
Hydrochloric acid	17.2	lb	17.2	kg	
Sulfuric acid	9.20	lb	9.20	kg	
Energy					
Process Energy					
Electricity from grid	267	kWh	589	kWh	
Electricity from cogen	282	kWh	622	kWh	
Natural gas	1,220	ft^3	76.2	m^3	
Transportation Energy					
Pipeline - refinery products	7.77	ton·mi	25.0	tonne·km	
Rail	0.23	ton·mi	0.74	tonne·km	
Barge	40.4	ton·mi	130	tonne·km	
Truck	0.040	ton·mi	0.13	tonne·km	
Environmental Emissions					
Atmospheric Emissions					
Carbon monoxide	0.10	lb	0.10	kg	*
Chlorine	0.0035	lb	0.0035	kg	*
Methane, tetrachloro-, CFC-10	1.0E-06	lb	1.0E-06	kg	*
Particulates, < 2.5 um	1.0E-04	lb	1.0E-04	kg	*
Sulfuric acid	1.0E-05	lb	1.0E-05	kg	*
Particulates, unspecified	0.010	lb	0.010	kg	*
Particulates, > 2.5 um, and < 10um	1.0E-04	lb	1.0E-04	kg	*
Waterborne Releases					
Suspended solids, unspecified	0.010	lb	0.010	kg	*
Zinc	1.0E-05	lb	1.0E-05	kg	*
Copper	1.0E-06	lb	1.0E-06	kg	*
Potassium	0.10	lb	0.10	kg	*
Chlorine	1.0E-05	lb	1.0E-05	kg	*
Chloride	1.0E-04	lb	1.0E-04	kg	*
Chloroform	1.0E-05	lb	1.0E-05	kg	*
TOC, Total Organic Carbon	0.0010	lb	0.0010	kg	*
Solid Wastes					
Solid waste, process to landfill	0.66	lb	0.66	kg	
Water Consumption	116	gal	970	l	

* To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by the order of magnitude of the average.

Source: Primary Data (2021a)

Table 17. LCI Data for the Production of Sodium Hydroxide Using the Membrane Cell Technology

	1,000 lb		1,000 kg		
Material Inputs					
Sodium chloride, brine solution	671	lb	671	kg	
Hydrochloric acid	17.2	lb	17.2	kg	
Energy					
Process Energy					
Electricity from grid	272	kWh	600	kWh	
Electricity from cogen	278	kWh	613	kWh	
Natural gas	1,222	ft^3	76.3	m^3	
Transportation Energy					
Pipeline - refinery products	7.77	ton·mi	25.0	tonne·km	
Rail	0.23	ton·mi	0.74	tonne·km	
Barge	40.4	ton·mi	130	tonne·km	
Truck	0.040	ton·mi	0.13	tonne·km	
Environmental Emissions					
Atmospheric Emissions					
Carbon monoxide	0.10	lb	0.10	kg	*
Particulates, < 2.5 um	1.0E-04	lb	1.0E-04	kg	*
Particulates, unspecified	0.010	lb	0.010	kg	*
Particulates, > 2.5 um, and < 10um	1.0E-04	lb	1.0E-04	kg	*
Sodium hydroxide	1.0E-04	lb	1.0E-04	kg	*
Waterborne Releases					
Suspended solids, unspecified	0.010	lb	0.010	kg	*
Zinc	1.0E-05	lb	1.0E-05	kg	*
Copper	1.0E-06	lb	1.0E-06	kg	*
Potassium	0.10	lb	0.10	kg	*
TOC, Total Organic Carbon	0.0010	lb	0.0010	kg	*
Solid Wastes					
Solid waste, process to landfill	0.66	lb	0.66	kg	
Water Consumption	115	gal	961	l	

* To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by the order of magnitude of the average.

Source: Primary Data (2021a)

Table 18. LCI Data for the Production of Hydrogen Using the Membrane Cell Technology

	1,000 lb		1,000 kg		
Material Inputs					
Sodium chloride, brine solution (1)	0	lb	0	kg	
Hydrochloric acid	22.5	lb	22.5	kg	
Energy					
Process Energy					
Electricity from grid	597	kWh	1,317	kWh	
Electricity from cogen	16.8	kWh	37.0	kWh	
Natural gas	147	ft^3	9.20	m^3	
Transportation Energy					
Pipeline - refinery products	0.40	ton·mi	1.30	tonne·km	
Rail	1.30	ton·mi	4.18	tonne·km	
Barge	230	ton·mi	740	tonne·km	
Truck	0.15	ton·mi	0.48	tonne·km	
Environmental Emissions					
Atmospheric Emissions					
Carbon monoxide	0.10	lb	0.10	kg	*
Particulates, < 2.5 um	1.0E-07	lb	1.0E-07	kg	*
Particulates, unspecified	0.010	lb	0.010	kg	*
Particulates, > 2.5 um, and < 10um	1.0E-07	lb	1.0E-07	kg	*
Waterborne Releases					
Suspended solids, unspecified	0.010	lb	0.010	kg	*
Zinc	1.0E-06	lb	1.0E-06	kg	*
Copper	1.0E-07	lb	1.0E-07	kg	*
Potassium	0.010	lb	0.010	kg	*
TOC, Total Organic Carbon	1.0E-04	lb	1.0E-04	kg	*
Solid Wastes					
Solid waste, process to landfill	3.70	lb	3.70	kg	
Water Consumption	97.1	gal	810	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.

(1) Due to the use of stoichiometric allocation, no sodium chloride is allocated to hydrogen production.

Source: Primary Data (2021a)

Table 19. LCI Data for the Production of Hydrochloric Acid (50% solution)

	1,000 lb		1,000 kg		
Inputs from Technosphere (1)					
Energy					
Process Energy					
Electricity from grid	150	kWh	330	kWh	
Environmental Emissions					
Atmospheric Emissions					
Chlorine	1.9	lb	1.9	kg	
Hydrochloric Acid	0.0010	lb	0.0010	kg	*

(1) The inputs of hydrogen and chlorine come from the Chlor-alkali plant, where the Hydrochloric acid created is used. As the inputs come from the chlor-alkali plant and the product is used within the plant, no inputs from the technosphere are included. This dataset should only be used as an input to the Chlor-alkali plant.

* To indicate known emissions while protecting the confidentiality of individual company responses, the emission is reported only by the order of magnitude of the average.

Source: Althaus (2007b), Primary Data (2021a), and Franklin (2021b).

ETHYLENE DICHLORIDE (EDC)/VINYL CHLORIDE MONOMER (VCM) PRODUCTION

The manufacture of ethylene dichloride may be through direct chlorination or oxychlorination. All data providers used a mix of both technologies in parallel to create EDC.

The manufacture of ethylene dichloride begins with the direct chlorination of ethylene. Ethylene is chlorinated in the liquid phase. A ferric chloride catalyst is commonly used to drive the reaction. Direct chlorination is an exothermic reaction. It requires heat removal to control the temperature.

$$CH_2{=}CH_2 + Cl_2 \rightarrow ClCH_2CH_2Cl \qquad \text{(Reaction 1-Direct Chlorination)}$$

The crude product from the reactor is then purified by distillation to yield ethylene dichloride. (Cowfer, 2006)

Using the oxychlorination process requires a higher capital investment and operating costs and produces a less pure EDC product. This process is used as it consumes the byproduct hydrochloric acid that is generated during EDC pyrolysis. The ethylene is reacted with HCl and air or oxygen and is carried out in the vapor phase in a fixed- or fluidized-bed reactor using a catalyst. This is also a highly exothermic reaction and requires good temperature control to assure efficient EDC production. (Cowfer, 2006)

$$CH_2{=}CH_2 + 2HCl + \tfrac{1}{2}O_2 \rightarrow ClCH_2CH_2Cl + H_2O \qquad \text{(Reaction 2-Oxychlorination)}$$

Once the EDC is created by either direct chlorination or oxychlorination, it must be purified as a number of byproducts are within the EDC. For direct chlorination, this may only be the removal of a small amount of ferric chloride. The EDC from oxychlorination is less pure and is normally purified by distillation. The recovered EDC stream can be recycled back to the chlorination process.

Vinyl chloride monomer (VCM) is produced almost exclusively by thermal cracking (dehydrochlorination) of ethylene dichloride. The ethylene dichloride is fed to the pyrolysis unit where separation of HCl from the VCM is performed through fractional distillation at noncryogenic temperatures. The HCl from this process is fed back to the oxychlorination reaction. Impurities usually remain with the unreacted EDC Unreacted ethylene dichloride is separated from the VCM. Impurities usually remain with the unreacted EDC and are sent to EDC purification for removal. Chlorine or carbon tetrachloride are sometimes added to the reactor feed so as to suppress the creation of methyl chloride. (Cowfer, 2006)

$$2ClCH_2CH_2Cl \rightarrow 2CH_2{=}CHCl + 2HCl \qquad \text{(Reaction 3-Pyrolysis)}$$

Ethylene dichloride data was collected with VCM data and are included within the VCM dataset. LCI data for the production of EDC/VCM were collected from three producers (three plants) in North America – all in the United States. All companies provided data for the year 2015. After reviewing individual company data in comparison to the average, each manufacturer verified data from 2015 was representative of an average year for EDC/VCM production at their company. Small amounts of heavy ends from the distillation and excess hydrochloric acid were the only coproducts. Mass allocation was used to allocate all inputs and outputs to each product and co-product.

Primary data were collected from EDC/VCM 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 representative of an average year for EDC/VCM production at their company.

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

After review of the emissions data, the Vinyl Institute (VI) requested that a few emissions that were not supplied by all data providers be taken from the Toxic Release Inventory (TRI) database. VI provided guidance on assumptions and production amounts of PVC from suspension technology used to calculate these emissions. More information on these assumptions can be found in the *TRI Emissions Use for EDC/VCM and PVC Resin* section of the methodology chapter. These emissions include the following air and water emissions: VCM, EDC, carbon tetrachloride, methyl chloride, 1,1,1 trichloromethane, and dioxins (in grams TEQ).

The energy requirements and environmental emissions for the production of 1,000 lb and 1,000 kg of EDC/VCM are shown in Table 20. In the case of some emissions, data was provided by fewer than the 3 producers. To indicate known emissions while protecting the confidentiality of individual company responses, some emissions are reported only by the order of magnitude of the average.

Table 20. LCI Data for the Production of EDC/VCM

	1,000 lb		1,000 kg		
Material Inputs					
Ethylene	490	lb	490	kg	
Oxygen	160	lb	160	kg	
Chlorine	600	lb	600	kg	
Nitrogen	73.0	lb	73.0	kg	
Sodium Hydroxide	6.50	lb	6.50	kg	
Energy					
Process Energy					
Electricity from grid	24.5	kWh	54.0	kWh	
Electricity from cogen	118	kWh	260	kWh	
Natural gas	2,243	ft^3	140	m^3	
Hydrogen	1.50	lb	1.50	kg	
Transportation Energy					
Pipeline - refinery products	5.28	ton·mi	17.0	tonne·km	
Pipeline - gas products	1.86	ton·mi	6.00	tonne·km	
Rail	19.9	ton·mi	64.0	tonne·km	
Environmental Emissions					
Atmospheric Emissions					
Carbon monoxide	0.037	lb	0.037	kg	*
Chlorine	0.010	lb	0.010	kg	*
Nitrogen oxides	0.20	lb	0.20	kg	
Organic substances, unspecified	0.0010	lb	0.0010	kg	*
Particulates, unspecified	0.0010	lb	0.0010	kg	*
Particulates, < 2.5 um	0.010	lb	0.010	kg	*
Particulates, > 2.5 um, and < 10um	0.0010	lb	0.0010	kg	*
NMHC, non-methane hydrocarbons	0.0010	lb	0.0010	kg	*
Sulfur oxides	0.0001	lb	0.0001	kg	*
Carbon dioxide, fossil	10.0	lb	10.0	kg	*
Ammonia	0.010	lb	0.010	kg	*
Vinyl Chloride	0.011	lb	0.011	kg	**
Ethane, 1,2-dichloro-	0.024	lb	0.024	kg	**
1,3 Butadiene	1.0E-07	lb	1.0E-07	kg	*
Benzene	1.0E-05	lb	1.0E-05	kg	*
Cumene	1.0E-04	lb	1.0E-04	kg	*

Table 20. LCI Data for the Production of EDC/VCM (continued)

	1,000 lb		1,000 kg		
Atmospheric Emissions (Cont)					
Toluene	1.0E-06	lb	1.0E-06	kg	*
Chloroform	0.0031	lb	0.0031	kg	**
Ethylene	0.0010	lb	0.0010	kg	*
Propylene	0.010	lb	0.010	kg	*
VOC, volatile organic compounds, unspecified origin	0.010	lb	0.010	kg	*
Methane, tetrachloro (CFC-10)	0.0028	lb	0.0028	kg	**
Methane, monochloro (R-40)	8.9E-04	lb	8.9E-04	kg	**
Dioxins (unspecified)	2.0E-10	lb (TEQ)	2.0E-07	g (TEQ)	**
Waterborne Releases					
Copper compounds	1.0E-05	lb	1.0E-05	kg	*
Suspended solids, unspecified	0.0010	lb	1.0E-03	kg	*
Ammonia	1.0E-05	lb	1.0E-05	kg	*
Nitrate compounds	0.0010	lb	1.0E-03	kg	*
vinyl chloride	3.8E-10	lb	3.8E-10	kg	**
Chloroform	6.8E-06	lb	6.8E-06	kg	**
BOD5, Biological Oxygen Demand	0.0010	lb	1.0E-03	kg	*
Methyl chloride	9.4E-06	lb	9.4E-06	kg	**
Ethane, 1,2-dichloro-	1.2E-04	lb	1.2E-04	kg	**
Carbon tetrachloride	7.0E-06	lb	7.0E-06	kg	**
Dioxins (unspecified)	6.5E-10	lb (TEQ)	6.5E-07	g (TEQ)	**
Solid Wastes					
Solid waste, process to landfill	1.90	lb	1.90	kg	
Solid waste, process to incineration	0.0190	lb	0.02	kg	
Hazardous waste to landfill	0.065	lb	0.07	kg	
Hazardous waste sold for recycling or reuse	0.016	lb	0.02	kg	
Hazardous waste to incineration	0.02	lb	0.02	kg	
Water Consumption	168	gal	1,400	l	

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* 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.

** Due to limited data availability, the Toxic Release Inventory (TRI) data was used in place of collected data from EDC/VCM data collectors for the following emissions: vinyl chloride, ethylene dichloride, carbon tetrachloride, 111 trichloroethane (chloroform), methyl chloride, and dioxins. The Vinyl Institute provided the amount of EDC/VCM production in 2015. The Vinyl Institute also provided estimates for the percentage of each emission coming from the EDC/VCM production versus the PVC production. Dioxin amounts were calculated as Toxic Equivalent Values (TEQ).

Source: Primary Data (2021b), Toxic Release Inventory (2015)

POLYVINYL CHLORIDE (PVC) PRODUCTION

The polymerization of polyvinyl chloride resin from vinyl chloride monomer may be produced by either suspension, emulsion/dispersion, or mass/bulk processes. The most common (estimated 80%) of these in North America is the suspension polymerization (Ford, 2019). The emulsion polymerization is frequently used for specialized PVC. This analysis only provides LCI data for PVC using the suspension polymerization.

Vinyl chloride (VCM) plants are normally at the same site as the PVC plants, which allows the VCM to be piped to the PVC plant. Initiators and dispersing agents are also required for the polymerization to PVC but are small amounts overall and not included in the LCI inputs. VCM droplets are dispersed in water to allow the reaction to occur in a liquid phase. An initiator is used to being the polymerization of VCM, which is an exothermic reaction and uses a cooling system for temperature control. The polymerization generally is carried out in a nitrogen atmosphere in large, agitated reactors. The polymer is precipitated out of the monomer to an estimated 90 percent conversion. The slurry is passed through a column feed tank and stripper at a lower pressure where the excess VCM is removed, recovered, and recycled back to the polymerization reactor. The PVC slurry is dried until its moisture content falls to 0.2-0.3 percent range. (Chem Eng, 2021) The polymer may be blended with additives and modifiers. No plasticizers or other additives, as well as compounding of these materials, are included in this analysis.

Four PVC producers (six plants) provided data. Three PVC manufacturers (four plants) provided data for the production of PVC using suspension polymerization. One company (two plants) submitted data for production of PVC using a combination of technologies; suspension, dispersion and microdispersion. Because the overall average is significantly affected when including the combination of technologies to produce PVC, data from this company is excluded. All companies provided data for the years 2015. A weighted average was calculated from the data collected and used to develop the LCA model. Only small amounts of off-spec product are coproducts of PVC resin production, and a mass basis was used to allocate burdens among coproducts.

PVC resin producers that provided data considered the technology at their facility either average to state-of-the-art. All data represent suspension polymerization only.

Primary data were collected from PVC 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 PVC production in North America.

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

After review of the emissions data, the Vinyl Institute (VI) requested that a few emissions that were not supplied by all data providers be taken from the Toxic Release Inventory (TRI) database. VI provided guidance on assumptions and production amounts of PVC from suspension technology used to calculate these emissions. More information on these assumptions can be found in the *TRI Emissions Use for EDC/VCM and PVC Resin* section of the methodology chapter. These emissions include the following air and water emissions: VCM, EDC, carbon tetrachloride, methyl chloride, 1,1,1 trichloromethane, and dioxins (in grams TEQ).

Table 21 shows the averaged energy and emissions data for the production of 1,000 pounds and 1,000 kilograms of PVC resin. In the case of some emissions, data was provided by fewer than the 3 producers. To indicate known emissions while protecting the confidentiality of individual company responses, some emissions are reported only by the order of magnitude of the average.

Table 21. LCI Data for the Production of Polyvinyl Chloride (PVC)

	1,000 lb		1,000 kg		
Material Inputs					
EDC/VCM	997	lb	997	kg	
Energy					
Process Energy					
Electricity from grid	90.7	kWh	200	kWh	
Electricity from cogen	26.8	kWh	59.0	kWh	
Natural gas	1,009	ft^3	63.0	m^3	
Transportation Energy					
Pipeline -refinery products	3.42	ton·mi	11.0	tonne·km	
Rail	103	ton·mi	330	tonne·km	
Environmental Emissions					
Atmospheric Emissions					
Particulates, unspecified	0.010	lb	0.010	kg	*
Particulates, < 2.5 um	0.010	lb	0.010	kg	*
Particulates, > 2.5 um, and < 10um	0.010	lb	0.010	kg	*
Nitrogen oxides	1.0E-04	lb	1.0E-04	kg	*
NMHC, non-methane hydrocarbons	0.010	lb	0.010	kg	*
HFC (unspec.)	0.0010	lb	0.0010	kg	*
Aldehydes, unspecified	1.0E-05	lb	1.0E-05	kg	*
Ammonia	1.0E-04	lb	1.0E-04	kg	*
Organic substances, unspecified	0.0010	lb	0.0010	kg	*
Chlorine	1.0E-04	lb	1.0E-04	kg	*
Vinyl Chloride	0.020	lb	0.020	kg	**
Methanol	0.0010	lb	0.0010	kg	*
Methane, monochloro-, R-40	0.0013	lb	0.0013	kg	**
Ethyl Chloride	1.0E-04	lb	1.0E-04	kg	*
Dioxins (unspecified)	9.8E-12	lb (TEQ)	9.8E-09	g (TEQ)	**

Table 21. LCI Data for the Production of Polyvinyl Chloride (PVC) (Continued)

	1,000 lb		1,000 kg		
Waterborne Releases					
BOD5, Biological Oxygen Demand	0.0010	lb	0.0010	kg	*
COD, Chemical Oxygen Demand	0.010	lb	0.010	kg	*
Oils, unspecified	0.0010	lb	0.0010	kg	
Suspended solids, unspecified	0.020	lb	0.020	kg	*
Phosphate	1.0E-04	lb	1.0E-04	kg	*
Zinc	1.0E-05	lb	1.0E-05	kg	*
Ammonia	1.0E-04	lb	1.0E-04	kg	*
Nitrate compounds	0.010	lb	0.010	kg	*
TOC, Total Organic Carbon	0.0010	lb	0.0010	kg	
Vinyl Chloride	5.1E-10	lb	5.1E-10	kg	**
Dioxins (unspecified)	2.2E-12	lb (TEQ)	2.2E-09	g (TEQ)	**
Solid Wastes					
Solid waste, process to landfill	0.64	lb	0.64	kg	
Solid Waste Sold for Recycling or Reuse	0.44	lb	0.44	kg	
Hazardous waste to incineration	0.014	lb	0.014	kg	
Water Consumption	395	gal	3,300	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.

** Due to limited data availability, the Toxic Release Inventory (TRI) data was used in place of collected data from PVC data collectors for the following emissions: vinyl chloride, methyl chloride, and dioxins. The Vinyl Institute provided the amount of PVC production from suspension technology in 2015. The Vinyl Institute also provided estimates for the percentage of each emission coming from the EDC/VCM production versus the PVC production. Dioxin amounts were calculated as Toxic Equivalent Values (TEQ).

Source: Primary Data (2021c), Toxic Release Inventory (2015)

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