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

UPDATE TO THE PVC SECTION OF THE REPORT: CRADLE-TO-GATE LIFE CYCLE INVENTORY OF NINE PLASTIC RESINS AND FOUR POLYURETHANE PRECURSORS

Submitted to:

**THE PLASTICS DIVISION OF
THE AMERICAN CHEMISTRY COUNCIL**

By:

**Franklin Associates,
A Division of ERG**

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FRANKLIN Associates
A Division of ERG

PREFACE

This cradle-to-resin LCI study of PVC was updated for the Plastics Division of the American Chemistry Council (ACC). Mike Levy was the project coordinator for the Plastics Division of the ACC. The report was made possible through the cooperation of ACC member companies and non-member companies who provided data on the production of PVC resin, EDC/VCM, and chlorine. This report is an update to Chapter 9 and Appendix I of the final revised report for all 9 plastic resins dated August, 2011. Updates included the change in technology percentages of the chlorine production and an update in TRI data. Some changes were made due to the intense scrutiny of all data as it was provided to the NREL U.S. LCI Database. A list of differences between this separate PVC report and the previous full report can be found in the Introduction.

Eastern Research Group, Franklin Associates Division, carried out the work as an independent contractor for this project. Melissa Huff was Project Manager. Significant contributions were made by Anne Marie Molen and Lori Snook.

Franklin Associates and the Plastics Division of the American Chemistry Council are grateful to all of the companies and associations that participated in the LCI data collection process. We would also like to thank Richard Krock of The Vinyl Institute.

Comparisons between plastic resins should not be made on the basis of cradle-to-resin/precursor results, as the ISO 14040 series of standards require that comparisons of product systems must be made on the basis of equivalent function, and functional equivalence cannot be established without including fabrication of the resin or precursor into a functional product.

December, 2013

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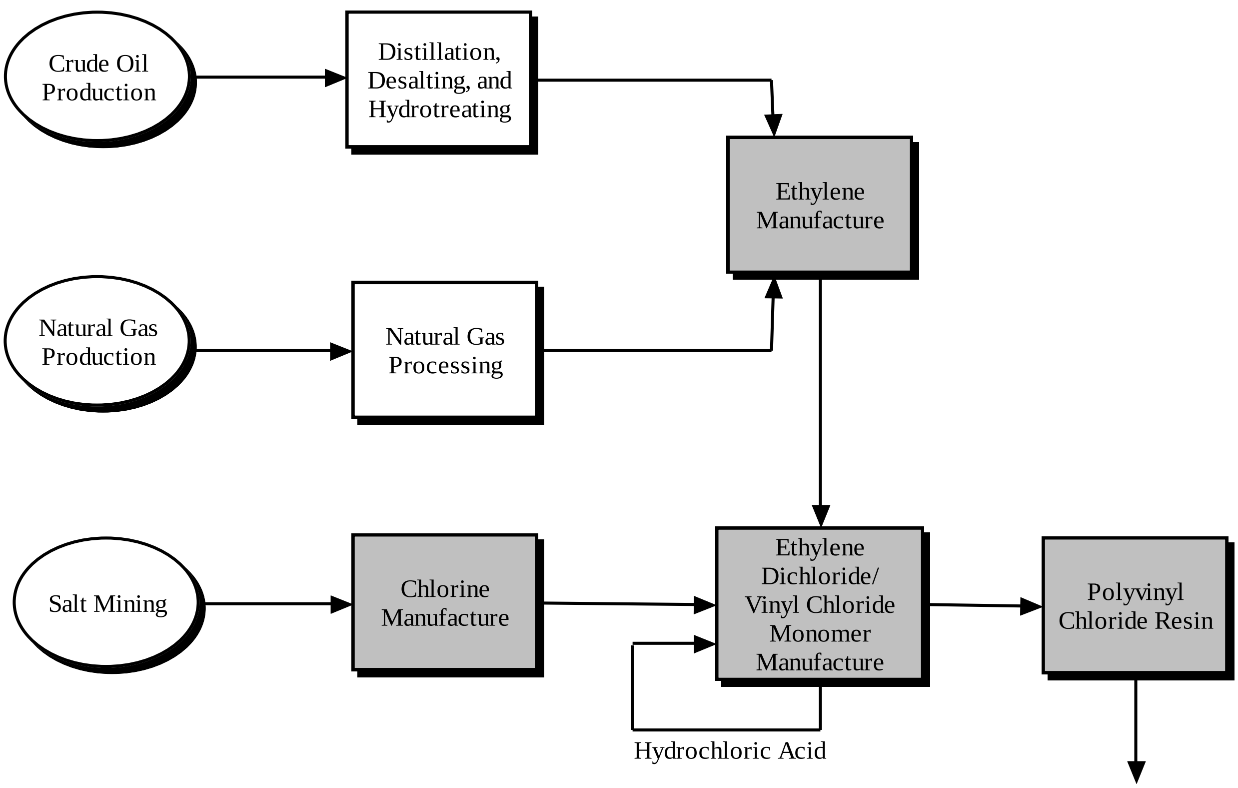
CRADLE-TO-RESIN LIFE CYCLE INVENTORY OF POLYVINYL CHLORIDE (PVC)

1. INTRODUCTION

This report presents LCI results for the production of polyvinyl chloride (PVC) resin (cradle-to-resin). The results are given on the bases of 1,000 pounds and 1,000 kilograms of PVC resin.

Figure 1 presents the flow diagram for the production of PVC resin. Process descriptions and individual process tables for each box shown in the flow diagram can be found in the Appendix at the end of this document.

No fillers, additives, or plasticizers are included in this analysis; therefore, no compounding process is included.



Note: Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

Figure 1. Flow Diagram for the Manufacture of Polyvinyl Chloride (PVC) Resin

Primary data was collected for olefins, chlorine/caustic soda, EDC/VCM, and PVC resin production. A weighted average using production quantities was calculated from the olefins production data collected from three leading producers (8 thermal cracking units) in North America. As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. The captured production amount is approximately 30 percent of the available capacity for olefin production. Numerous coproduct streams are produced from the olefins hydrocracker. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The separate appendices provide an in-depth discussion of this allocation. A mass basis was used to allocate the credit to the remaining material coproducts.

The chlorine/caustic data collected for this module represent 1 producer and 3 plants in the U.S. Besides this recently collected data, 2 diaphragm cell datasets and 2 mercury cell datasets were used from the early 1990s. According to discussions with The Vinyl Institute, no chlorine produced from mercury cell technology is going into EDC production as of 2012. Only the collected datasets diaphragm/membrane cell technology. As of 2003 there were 20 chlorine/caustic producers and 41 chlorine/caustic plants in the U.S. for the three standard technologies. The captured production amount is approximately 30 percent of the available capacity for all chlorine production in the U.S. Caustic soda and hydrogen are the coproducts produced with chlorine. A mass basis was used to allocate the credit to the coproducts.

A weighted average using production amounts was calculated from the EDC/VCM production data from three plants collected from three leading producers in North America. As of 2003, there were 8 VCM producers and 12 VCM plants in the U.S. The captured production amount is approximately 50 percent of the available capacity for VCM production in the U.S. Dichloroethane is produced as a coproduct during this process. A mass basis was used to allocate the credit for the coproduct.

A weighted average using production amounts was calculated from the PVC production data from three plants collected from three leading producers in North America. As of 2003, there were 12 PVC producers and 25 PVC plants in the U.S. The captured production amount is approximately 35 percent of the available capacity for PVC production in the U.S. and Canada. Scrap resin (e.g. off-spec) is produced as a coproduct during this process. A mass basis was used to allocate the credit for the coproduct.

2. METHODOLOGY

The methodology used in this report is identical to that described in the previous consolidated report, Cradle-to-Gate Life Cycle Analysis of Nine Plastic Resins and Four Polyurethane Precursors, as released in August, 2011. At this time, refer to that document for discussion of the methodology used in this report.

3. RESULTS TABLES

The average gross energy required to produce PVC resin is 23.7 million Btu per 1,000 pounds of resin or 55.1 GJ per 1,000 kilograms of resin. Table 1 and Table 2 show the breakdown of energy requirements for the production of PVC resin by category and source, respectively. Precombustion energy (the energy used to extract and process fuels used for process energy and transportation energy) is included in the results shown in these tables. Table A-1 in the Appendix attached provides the aggregated unit process energy (cradle-to-resin) for the production of PVC resin. Natural gas and petroleum used as raw material inputs for the production of PVC, reported as energy of material resource in Table 1, are included in the totals for natural gas and petroleum energy in Table 2. Petroleum-based fuels (e.g. diesel fuel) are the dominant energy source for transportation. Non-fossil sources, such as hydropower, nuclear and other (geothermal, wind, etc.) shown in Table 2 are used to generate purchased electricity along with the fossil fuels.

Table 3 shows the weight of solid waste generated during the production of PVC resin. The process solid waste, those wastes produced directly from the cradle-to-resin processes, includes wastes that are incinerated both for disposal and for waste-to-energy, as well as landfilled. These categories have been provided separately. Solid waste from fuel production and combustion is also presented.

Total atmospheric emissions are shown in

Table 4. These totals include both process and fuel-related emissions. Process emissions are those released directly from the sequence of processes that are used to extract, transform, fabricate, or otherwise affect changes on a material or product during its life cycle, while fuel-related emissions are those associated with the combustion of fuels used for process energy and transportation energy.

Table 5 provides a greenhouse gas (GHG) summary for the production of PVC resin. The primary three atmospheric emissions reported in this analysis that contribute to global warming are fossil fuel-derived carbon dioxide, methane, and nitrous oxide. (Non-fossil carbon dioxide emissions, such as those from the burning of wood, are considered part of the natural carbon cycle and are not considered a net contributor to global warming.) The 100-year global warming potential for each of these substances as reported in the Intergovernmental Panel on Climate Change (IPCC) 2007 report are shown in a note at the bottom of Table 5. The global warming potential represents the relative global warming contribution of a pound of a particular greenhouse gas compared to a pound of carbon dioxide. The weights of each of the contributing emissions in

Table 4 are multiplied by their global warming potential and shown in Table 5.

Total waterborne emissions are shown in Table 6. These totals include both process and fuel-related emissions.

Table 1. Energy by Category for the Production of PVC Resin

	MMBtu per 1,000 pounds	GJ per 1,000 kilograms
Energy Category		
Process/Transportation (1)	13.9	32.2
Energy of Material Resource	9.8	22.8
Total Energy	**23.7**	**55.1**
Energy Category (Percent)		
Process	59%	59%
Energy of Material Resource	41%	41%
Total	100%	100%

(1) Process energy includes recovered energy, which is shown as a credit.

Source: Franklin Associates, A Division of ERG

Table 2. Energy Profile for the Production of PVC Resin

	MM Btu per 1,000 pounds	GJ per 1,000 kilograms
Energy Source		
Natural Gas	18.1	42.2
Petroleum	2.43	5.65
Coal	2.24	5.20
Hydropower	0.089	0.21
Nuclear	0.77	1.79
Wood	0.0019	0.0045
Other	0.010	0.022
Recovered Energy (1)	-0.0056	-0.013
Total Energy	**23.7**	**55.1**
Energy Source (Percent)		
Natural Gas	76%	76%
Petroleum	10%	10%
Coal	10%	10%
Hydropower	0.4%	0.4%
Nuclear	3%	3%
Wood	0%	0%
Other	1%	1%
Total	100%	100%

(1) Recovered energy represents the recovery of energy as steam or condesate. Because this energy will be used by other processes, it is shown as a negative entry (credit).

Source: Franklin Associates, A Division of ERG

Table 3. Solid Waste by Weight for the Production of PVC Resin

	lb per 1,000 pounds	kg per 1,000 kilograms
Solid Wastes By Weight		
Process		
Landfilled	13.8	13.8
Incinerated	5.68	5.68
Waste-to-Energy	22.0	22.0
Fuel	98.4	98.4
Total	**140**	**140**
Weight Percent by Category		
Process		
Landfilled	10%	10%
Incinerated	4%	4%
Waste-to-Energy	16%	16%
Fuel	70%	70%
Total	**100%**	**100%**

Source: Franklin Associates, A Division of ERG

Table 4. Atmospheric Emissions for the Production of PVC Resin (lb per 1,000 lb or kg per 1,000 kg) (page 1 of 2)

Atmospheric Emissions		
2-Chloroacetophenone		6.9E-08
5-methyl Chrysene		2.5E-09
Acenaphthene		5.8E-08
Acenaphthylene		2.8E-08
Acetaldehyde		1.7E-05
Acetophenone		1.5E-07
Aldehydes, unspecified		9.9E-05
Ammonia		0.0027
Ammonium chloride		2.9E-04
Anthracene		2.4E-08
Antimony		2.3E-06
Arsenic		5.0E-05
Benzene		0.081
Benzene, chloro-		2.2E-07
Benzene, ethyl-		0.010
Benzo(a)anthracene		9.1E-09
Benzo(a)pyrene		4.3E-09
Benzo(b,j,k)fluoranthene		1.2E-08
Benzo(ghi)perylene		3.1E-09
Benzyl chloride		6.9E-06
Beryllium		2.9E-06
Biphenyl		1.9E-07
Bromoform		3.9E-07
Butadiene		5.7E-07
Cadmium		1.7E-05
Carbon dioxide, fossil		1,938
Carbon disulfide		1.3E-06
Carbon monoxide		1.70
Carbon monoxide, fossil		0.87
Chlorine		0.012
Chloroform		5.8E-07
Chromium		4.3E-05
Chromium VI		8.9E-06
Chrysene		1.1E-08
Cobalt		2.2E-05
Copper		8.3E-07
Cumene		5.2E-08
Cyanide		2.5E-05
Dinitrogen monoxide		0.039
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	(1)	3.3E-10
Ethane, 1,1,1-trichloro-, HCFC-140		2.0E-07
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a		4.9E-05
Ethane, 1,2-dibromo-		1.2E-08
Ethane, 1,2-dichloro-		4.0E-07
Ethane, 1,2-dichloro-1,1,2-trifluoro-, HCFC-123		4.9E-05
Ethane, chloro-		4.2E-07
Ethene, chloro-		0.032
Ethene, tetrachloro-		5.1E-06
Ethylene dibromide		5.3E-07
Fluoranthene		8.0E-08
Fluorene		1.0E-07
Fluoride		4.5E-04
Formaldehyde		8.0E-04
Furan		4.6E-10
Hexane		6.6E-07
Hydrazine, methyl-		1.7E-06
Hydrocarbons, unspecified		0.0017
Hydrogen		0.0018
Hydrogen chloride		0.13

Table 4. Atmospheric Emissions for the Production of PVC Resin (lb per 1,000 lb or kg per 1,000 kg) (page 2 of 2)

		(lb per 1,000 lb or kg per 1,000 kg)
Hydrogen fluoride		0.017
Indeno(1,2,3-cd)pyrene		6.9E-09
Isophorone		5.7E-06
Kerosene		1.4E-04
Lead		8.7E-05
Magnesium		0.0012
Manganese		6.3E-05
Mercaptans, unspecified		0.0021
Mercury		2.4E-05
Methacrylic acid, methyl ester		2.0E-07
Methane		0.84
Methane, bromo-, Halon 1001		1.6E-06
Methane, chlorodifluoro-, HCFC-22		0.0010
Methane, chlorotrifluoro-, CFC-13		2.7E-06
Methane, dichloro-, HCC-30		4.5E-05
Methane, fossil		11.6
Methane, monochloro-, R-40		5.2E-06
Methane, tetrachloro-, CFC-10		1.0E-04
Methyl ethyl ketone		3.9E-06
Naphthalene		8.5E-06
Nickel		1.8E-04
Nitrogen oxides		2.98
NMVOC, non-methane volatile organic compounds, unspecified origin		0.30
Organic acids		1.1E-06
Organic substances, unspecified	(2)	0.047
PAH, polycyclic aromatic hydrocarbons		2.5E-06
Particulates, < 10 um		0.40
Particulates, < 2.5 um		0.12
Particulates, > 2.5 um, and < 10um		0.11
Particulates, unspecified		0.49
Phenanthrene		3.1E-07
Phenol		1.6E-07
Phenols, unspecified		1.1E-05
Phthalate, dioctyl-		7.2E-07
Polycyclic organic matter, unspecified		6.9E-06
Propanal		3.8E-06
Propene		3.8E-05
Pyrene		3.7E-08
Radioactive species, unspecified		5.8E+06
Radionuclides (Including Radon)	(3)	0.0077
Selenium		1.5E-04
Styrene		2.5E-07
Sulfur dioxide		4.93
Sulfur oxides		0.60
Sulfuric acid, dimethyl ester		4.8E-07
t-Butyl methyl ether		3.5E-07
Toluene		0.12
Toluene, 2,4-dinitro-		2.8E-09
Vinyl acetate		7.5E-08
VOC, volatile organic compounds		0.73
Xylene		0.072
Zinc		5.5E-07

(1) This emission was provided by the Vinyl Institute based on 2011 Dioxin TRI values and listed EDC capacity for the site assuming an operating rate at EDC capacity. Molar ratios were used to convert to units for PVC. These amounts were calculated as toxic equivalent values (TEQ).

(2) This emission category contains small amounts of EDC and VCM as well as other hydrocarbons which were not separated out by the data providers. These amounts may be overcounting the VCM emissions as the Vinyl Institute provided atmospheric VCM emissions for the production of EDC/VCM/PVC.

(3) The units for Radionuclides are Curies per 1,000 lbs of product. To convert the total Radionuclides to metric units use a conversion factor of 81569665 kbq/kg to get a total of 626,000 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

Table 5. Greenhouse Gas Summary for the Production of PVC Resin
(lb carbon dioxide equivalents per 1,000 lb of PVC or kg carbon dioxide equivalents per 1,000 kg of PVC)

	Total CO2 Equiv.
Carbon Dioxide - Fossil	1,938
Methane	310
Dinitrogen monoxide (Nitrous Oxide)	11.7
Methane, bromo-, Halon 1001 (Methyl Bromide)	7.9E-06
Methane, monochloro-, R-40 (Methyl Chloride)	9.8E-08
Trichloroethane	0
Chloroform	1.8E-05
Methane, dichloro-, HCC-30 (Methylene Chloride)	4.5E-04
Methane, tetrachloro-, CFC-10 (Carbon Tetrachloride)	0.14
Methane, chlorotrifluoro-, CFC-13 (CFC 13 Methane, trichlorofluoro-)	0.032
Ethane, 1,2-dichloro-1,1,2-trifluoro-, HCFC-123 (HCFC-123)	0.0038
Methane, chlorodifluoro-, HCFC-22 (HCFC-22)	1.81
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a, (HFC-134a)	0.070
Total	1,951

Note: The 100 year global warming potentials used in this table are as follows: fossil carbon dioxide--1, methane--25, nitrous oxide--298, methyl bromide--5, methyl chloride--16, trichloroethane--140, chloroform--30, methylene chloride--10, carbon tetrachloride--1400, CFC-013--11,700, HCFC-22--1810, HCFC-123--77, and HFC-134a--1430.

Source: Franklin Associates, A Division of ERG

Table 6. Waterborne Emissions for the Production of PVC Resin
(lb per 1,000 lb or kg per 1,000 kg)
(page 1 of 2)

Atmospheric Emissions		
2-Chloroacetophenone		6.9E-08
5-methyl Chrysene		2.5E-09
Acenaphthene		5.8E-08
Acenaphthylene		2.8E-08
Acetaldehyde		1.7E-05
Acetophenone		1.5E-07
Aldehydes, unspecified		9.9E-05
Ammonia		0.0027
Ammonium chloride		2.9E-04
Anthracene		2.4E-08
Antimony		2.3E-06
Arsenic		5.0E-05
Benzene		0.081
Benzene, chloro-		2.2E-07
Benzene, ethyl-		0.010
Benzo(a)anthracene		9.1E-09
Benzo(a)pyrene		4.3E-09
Benzo(b,j,k)fluoranthene		1.2E-08
Benzo(ghi)perylene		3.1E-09
Benzyl chloride		6.9E-06
Beryllium		2.9E-06
Biphenyl		1.9E-07
Bromoform		3.9E-07
Butadiene		5.7E-07
Cadmium		1.7E-05
Carbon dioxide, fossil		1,938
Carbon disulfide		1.3E-06
Carbon monoxide		1.70
Carbon monoxide, fossil		0.87
Chlorine		0.012
Chloroform		5.8E-07
Chromium		4.3E-05
Chromium VI		8.9E-06
Chrysene		1.1E-08
Cobalt		2.2E-05
Copper		8.3E-07
Cumene		5.2E-08
Cyanide		2.5E-05
Dinitrogen monoxide		0.039
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	(1)	3.3E-10
Ethane, 1,1,1-trichloro-, HCFC-140		2.0E-07
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a		4.9E-05
Ethane, 1,2-dibromo-		1.2E-08
Ethane, 1,2-dichloro-		4.0E-07
Ethane, 1,2-dichloro-1,1,2-trifluoro-, HCFC-123		4.9E-05
Ethane, chloro-		4.2E-07
Ethene, chloro-		0.032
Ethene, tetrachloro-		5.1E-06
Ethylene dibromide		5.3E-07
Fluoranthene		8.0E-08
Fluorene		1.0E-07
Fluoride		4.5E-04
Formaldehyde		8.0E-04
Furan		4.6E-10
Hexane		6.6E-07
Hydrazine, methyl-		1.7E-06
Hydrocarbons, unspecified		0.0017
Hydrogen		0.0018
Hydrogen chloride		0.13

Table 6. Waterborne Emissions for the Production of PVC Resin (lb per 1,000 lb or kg per 1,000 kg) (page 2 of 2)

Hydrogen fluoride		0.017
Indeno(1,2,3-cd)pyrene		6.9E-09
Isophorone		5.7E-06
Kerosene		1.4E-04
Lead		8.7E-05
Magnesium		0.0012
Manganese		6.3E-05
Mercaptans, unspecified		0.0021
Mercury		2.4E-05
Methacrylic acid, methyl ester		2.0E-07
Methane		0.84
Methane, bromo-, Halon 1001		1.6E-06
Methane, chlorodifluoro-, HCFC-22		0.0010
Methane, chlorotrifluoro-, CFC-13		2.7E-06
Methane, dichloro-, HCC-30		4.5E-05
Methane, fossil		11.6
Methane, monochloro-, R-40		5.2E-06
Methane, tetrachloro-, CFC-10		1.0E-04
Methyl ethyl ketone		3.9E-06
Naphthalene		8.5E-06
Nickel		1.8E-04
Nitrogen oxides		2.98
NMVOC, non-methane volatile organic compounds, unspecified origin		0.30
Organic acids		1.1E-06
Organic substances, unspecified	(2)	0.047
PAH, polycyclic aromatic hydrocarbons		2.5E-06
Particulates, < 10 um		0.40
Particulates, < 2.5 um		0.12
Particulates, > 2.5 um, and < 10um		0.11
Particulates, unspecified		0.49
Phenanthrene		3.1E-07
Phenol		1.6E-07
Phenols, unspecified		1.1E-05
Phthalate, dioctyl-		7.2E-07
Polycyclic organic matter, unspecified		6.9E-06
Propanal		3.8E-06
Propene		3.8E-05
Pyrene		3.7E-08
Radioactive species, unspecified		5.8E+06
Radionuclides (Including Radon)	(3)	0.0077
Selenium		1.5E-04
Styrene		2.5E-07
Sulfur dioxide		4.93
Sulfur oxides		0.60
Sulfuric acid, dimethyl ester		4.8E-07
t-Butyl methyl ether		3.5E-07
Toluene		0.12
Toluene, 2,4-dinitro-		2.8E-09
Vinyl acetate		7.5E-08
VOC, volatile organic compounds		0.73
Xylene		0.072
Zinc		5.5E-07

(1) This emission was provided by the Vinyl Institute based on 2011 Dioxin TRI values and listed EDC capacity for the site assuming an operating rate at EDC capacity. Molar ratios were used to convert to units for PVC. These amounts were calculated as toxic equivalent values (TEQ).

(2) This emission category contains small amounts of EDC and VCM as well as other hydrocarbons which were not separated out by the data providers. These amounts may be overcounting the VCM emissions as the Vinyl Institute provided atmospheric VCM emissions for the production of EDC/VCM/PVC.

(3) The units for Radionuclides are Curies per 1,000 lbs of product. To convert the total Radionuclides to metric units use a conversion factor of 81569665 kbq/kg to get a total of 626,000 kBq per 1,000 kgs of product.

Source: Franklin Associates, A Division of ERG

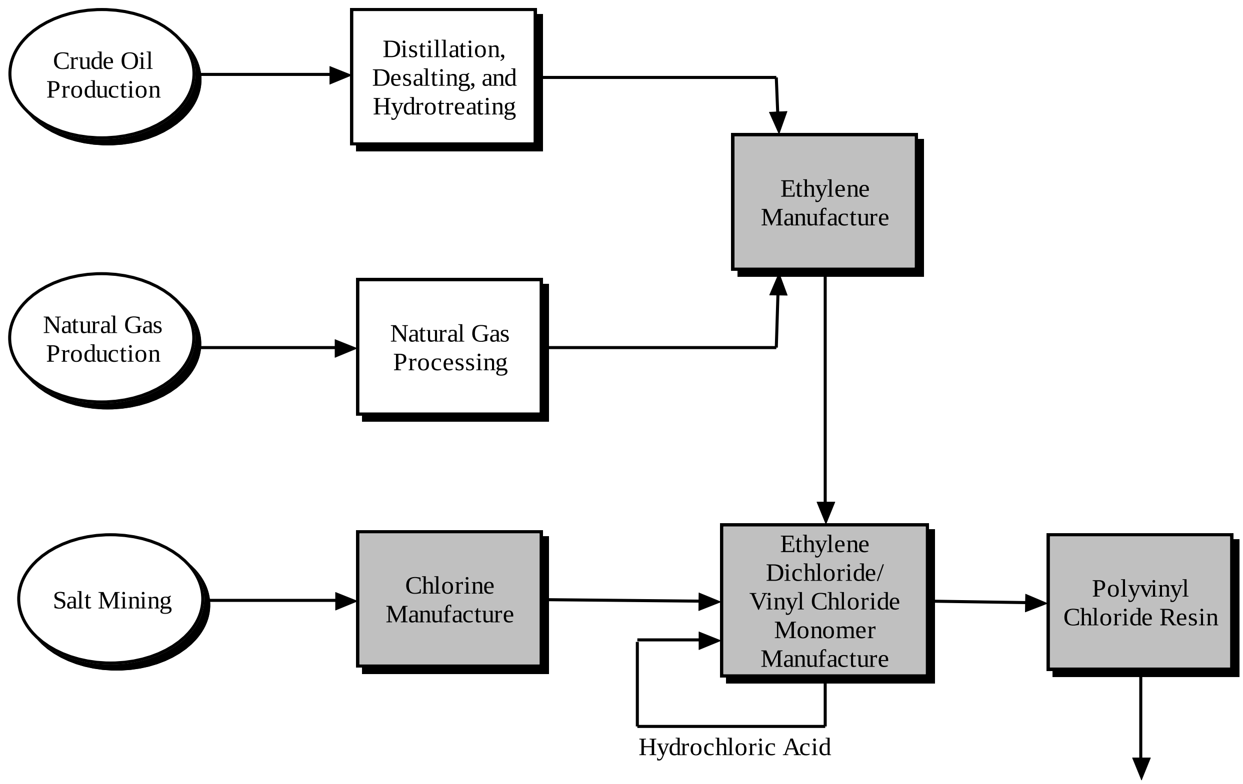
APPENDIX A.
PVC UNIT PROCESS INFORMATION

A.1. INTRODUCTION

This appendix discusses the manufacture of polyvinyl chloride (PVC) resin. Over half of the PVC produced is used to manufacture pipe and siding. Almost 15 billion pounds of PVC was produced in the U.S. and Canada in 2003 (Reference A-1). The material flow for PVC resin is shown in Figure A-1. The total unit process energy and emissions data (cradle-to-PVC) for PVC are displayed in Table A-1. Individual process tables on the bases of 1,000 pounds and 1,000 kilograms are also shown within this appendix. Processes that have been discussed in previous appendices have been omitted from this appendix. The following processes are included in this appendix:

- Crude Oil Extraction
- Oil Refining
- Natural Gas Production
- Natural Gas Processing
- Olefins (Ethylene) Manufacture
- Salt Mining
- Sodium Hydroxide or Chlorine Production
- Ethylene Dichloride (EDC) Production
- Vinyl Chloride Monomer (VCM) Production
- PVC Resin

No fillers, additives, or plasticizers are included in this analysis; therefore, no compounding process is included.



Note: Shaded boxes represent partial or complete data provided by manufacturers specifically for this analysis.

Figure A-1. Flow Diagram for the Manufacture of Polyvinyl Chloride (PVC) Resin

Table A-1. Data for the Production of Polyvinyl Chloride (PVC) Resin (Cradle-to-Resin) (page 1 of 3)

	English units (Basis: 1,000 lb)		Total Energy Thousand Btu	SI units (Basis: 1,000 kg)		Total Energy GigaJoules
Raw Materials						
Crude oil	86.8	lb		86.8	kg	
Natural Gas	378	lb		378	kg	
Salt	483	lb		483	kg	
Oxygen	140	lb		140	kg	
Energy Usage						
Energy of Material Resource						
Natural Gas	390		8,047	390		18.7
Petroleum	88		1,601	88		3.73
Total Resource			9,648			22.5
Process Energy						
Electricity (grid)	330	kwh	3,509	727	kwh	8.17
Electricity (cogeneration)	783	cu ft (2)	877	49	cu meters	2.04
Natural gas	5,753	cu ft	6,443	359	cu meters	15.0
LPG	0.011	gal	1.19	0.09	liter	0.0028
Bit./Sbit. Coal	19.6	lb	220	19.6	kg	0.51
Distillate oil	0.66	gal	105	5.49	liter	0.24
Residual oil	0.34	gal	58.0	2.82	liter	0.14
Gasoline	0.045	gal	6.38	0.37	liter	0.015
Diesel	0.0043	gal	0.68	0.036	liter	0.0016
Internal Offgas use (1)						
From Oil	11.8	lb	360	11.8	kg	0.84
From Natural Gas	53.6	lb	1,642	53.6	kg	3.82
Recovered Energy	5.59	thousand Btu	5.59	13.0	MJ	0.013
Total Process			13,216			30.8
Transportation Energy						
Combination truck	18.5	ton-miles		59.5	tonne-km	
Diesel	0.19	gal	30.8	1.62	liter	0.072
Rail	127	ton-miles		409	tonne-km	
Diesel	0.31	gal	50.0	2.63	liter	0.12
Barge	7.68	ton-miles		24.7	tonne-km	
Diesel	0.0061	gal	0.98	0.051	liter	0.0023
Residual oil	0.020	gal	3.51	0.17	liter	0.0082
Ocean freighter	728	ton-miles		2343	tonne-km	
Diesel	0.138	gal	21.97	1.15	liter	0.051
Residual	1.25	gal	213.7	10.39	liter	0.50
Pipeline-natural gas	401	ton-miles		1289	tonne-km	
Natural gas	276	cu ft	310	17.25	cu meter	0.72
Pipeline-petroleum products	112	ton-miles		362	tonne-km	
Electricity	2.45	kwh	25.1	5.40	kwh	0.058
Total Transportation			656			1.53
Environmental Emissions						
Atmospheric Emissions						
Ammonia	3.0E-04	lb		3.0E-04	kg	
Antimony	1.7E-07	lb		1.7E-07	kg	
Arsenic	2.2E-08	lb		2.2E-08	kg	
Benzene	0.036	lb		0.036	kg	
Carbon Dioxide - Fossil	63.7	lb		63.7	kg	
Carbon Monoxide	0.047	lb		0.047	kg	
Carbon Tetrachloride	1.0E-04	lb		1.0E-04	kg	
CFC 10 (Methane, tetrachloro-)	1.1E-07	lb		1.1E-07	kg	
CFC 13 (Methane, trichlorofluoro-)	1.8E-06	lb		1.8E-06	kg	

(1) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source.

(2) The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency. If offgas was used within the cogen plant, the energy amount is shown within the Internal Offgas use.

Table A-1 Data for the Production of Polyvinyl Chloride (PVC) Resin (Cradle-to-Resin) (page 2 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Environmental Emissions				
Atmospheric Emissions				
Ammonia	3.0E-04	lb	0.00	kg
Antimony	1.7E-07	lb	0.00	kg
Arsenic	2.2E-08	lb	0.00	kg
Benzene	3.6E-02	lb	0.04	kg
Carbon Monoxide	0.0064	lb	0.01	kg
Carbon Dioxide	63.6	lb	63.64	kg
Carbon Tetrachloride	1.9E-04	lb	0.00	kg
Chlorine	1.2E-02	lb	0.01	kg
Chromium	5.7E-08	lb	5.7E-08	kg
Dioxins (3)	1.1E-10	lb	1.1E-10	kg
Ethylbenzene	0.0043	lb	0.0043	kg
Ethylene Dibromide	3.6E-07	lb	3.6E-07	kg
HCFC-123	4.9E-05	lb	4.9E-05	kg
HCFC-22	0.0010	lb	0.0010	kg
HFC-134a	4.9E-05	lb	4.9E-05	kg
Hydrogen	0.0018	lb	0.0018	kg
Hydrogen Chloride	0.0029	lb	0.0029	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	0.057	lb	0.057	kg
Lead	6.1E-09	lb	6.1E-09	kg
Mercury	0.0E+00	lb	0.0E+00	kg
Methane	1.35	lb	1.35	kg
Nickel	4.8E-07	lb	4.8E-07	kg
Nitrogen Oxides	0.032	lb	0.032	kg
Non-Methane Hydrocarbons	0.041	lb	0.041	kg
Other Organics	0.046	lb	0.046	kg
Particulates (PM10)	0.060	lb	0.060	kg
Particulates (PM2.5)	0.0030	lb	0.0030	kg
Particulates (unspecified)	0.02	lb	0.02	kg
Polycyclic organic matter, unspecified	4.7E-06	lb	4.7E-06	kg
Sulfur Dioxide	0.02	lb	0.02	kg
Sulfur Oxides	0.7125	lb	0.7125	kg
Toluene	0.056	lb	0.056	kg
Vinyl Chloride (4)	0.039	lb	0.039	kg
VOC	0.29	lb	0.29	kg
Xylene	0.032	lb	0.032	kg
Solid Wastes				
Landfilled	14.0	lb	14.0	kg
Burned	2.41	lb	2.41	kg
Waste-to-Energy	00.0	lb	00.0	kg
Waterborne Wastes				
1-Methylfluorene	7.9E-09	lb	7.9E-09	kg
2,4-Dimethylphenol	3.2E-06	lb	3.2E-06	kg
2-Hexanone	7.5E-07	lb	7.5E-07	kg
2-Methylnaphthalene	1.8E-06	lb	1.8E-06	kg
4-Methyl-2-Pentanone	2.9E-07	lb	2.9E-07	kg
Acetone	7.0E-07	lb	7.0E-07	kg
Acid (benzoic)	1.2E-04	lb	1.2E-04	kg
Acid (hexanoic)	2.4E-05	lb	2.4E-05	kg
Alkylated benzenes	2.1E-05	lb	2.1E-05	kg
Alkylated fluorenes	1.2E-06	lb	1.2E-06	kg
Alkylated naphthalenes	3.5E-07	lb	3.5E-07	kg
Alkylated phenanthrenes	1.5E-07	lb	1.5E-07	kg
Aluminum	0.010	lb	0.010	kg
Ammonia	0.0035	lb	0.0035	kg
Antimony	6.6E-06	lb	6.6E-06	kg
Arsenic	2.2E-05	lb	2.2E-05	kg
Barium	0.14	lb	0.14	kg
Benzene	1.2E-04	lb	1.2E-04	kg
Beryllium	1.4E-06	lb	1.4E-06	kg
BOD	0.17	lb	0.17	kg
Boron	3.6E-04	lb	3.6E-04	kg
Bromide	1.4E-02	lb	0.014	kg
Cadmium	3.4E-06	lb	3.4E-06	kg
Calcium	2.3E-01	lb	0.23	kg
Chlorides	2.88	lb	2.88	kg
Chromium (unspecified)	3.8E-04	lb	3.8E-04	kg
Cobalt	2.5E-06	lb	2.5E-06	kg
COD	0.11	lb	0.11	kg
Copper	3.1E-05	lb	3.1E-05	kg

Table A-1 Data for the Production of Polyvinyl Chloride (PVC) Resin (Cradle-to-Resin) (page 3 of 3)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Cyanide	1.0E-06	lb	1.0E-06	kg
Cymene	7.0E-09	lb	0	kg
Dibenzofuran	1.3E-08	lb	1.3E-08	kg
Dibenzothiophene	1.1E-08	lb	1.1E-08	kg
Dioxins	2.9E-10	lb	2.9E-10	kg
Dissolved Solids	27.2	lb	27.2	kg
Ethylbenzene	1.1E-05	lb	1.1E-05	kg
Fluorine	5.8E-07	lb	5.8E-07	kg
Iron	0.019	lb	0.019	kg
Lead	5.8E-05	lb	5.8E-05	kg
Lead 210	1.2E-14	lb	1.2E-14	kg
Lithium	0.056	lb	0.056	kg
Magnesium	0.046	lb	0.046	kg
Manganese	6.6E-05	lb	6.6E-05	kg
Mercury	1.2E-07	lb	1.2E-07	kg
Methyl Chloride	2.8E-09	lb	2.8E-09	kg
Methyl Ethyl Ketone	5.6E-09	lb	5.6E-09	kg
Molybdenum	2.2E-06	lb	2.2E-06	kg
Naphthalene	2.1E-06	lb	2.1E-06	kg
n-Decane	3.3E-06	lb	3.3E-06	kg
n-Docosane	7.5E-08	lb	7.5E-08	kg
n-Dodecane	6.3E-06	lb	6.3E-06	kg
n-Eicosane	1.7E-06	lb	1.7E-06	kg
n-Hexacosane	4.7E-08	lb	4.7E-08	kg
n-Hexadecane	6.9E-06	lb	6.9E-06	kg
Nickel	2.7E-05	lb	2.7E-05	kg
Nitrates	0.010	lb	0.010	kg
n-Octadecane	1.7E-06	lb	1.7E-06	kg
m -Xylene	3.4E-06	lb	3.4E-06	kg
p -Xylene	1.2E-06	lb	1.2E-06	kg
o -Xylene	1.2E-06	lb	1.2E-06	kg
o-Cresol	3.3E-06	lb	3.3E-06	kg
Oil	0.0039	lb	0.0039	kg
p-Cresol	3.6E-06	lb	3.6E-06	kg
p-Cymene	6.6E-09	lb	6.6E-09	kg
Pentamethylbenzene	5.2E-09	lb	5.2E-09	kg
Phenanthrene	9.2E-08	lb	9.2E-08	kg
Phenol/ Phenolic Compounds	6.0E-04	lb	6.0E-04	kg
Tetradecane	2.7E-06	lb	2.7E-06	kg
Radium 226	4.1E-12	lb	4.1E-12	kg
Radium 228	2.1E-14	lb	2.1E-14	kg
Selenium	1.4E-06	lb	1.4E-06	kg
Silver	1.4E-04	lb	1.4E-04	kg
Sodium	0.66	lb	0.66	kg
Strontium	0.0062	lb	0.0062	kg
Styrene	4.5E-07	lb	4.5E-07	kg
Sulfates	0.0047	lb	0.0047	kg
Sulfides	1.6E-05	lb	1.6E-05	kg
Sulfur	2.9E-04	lb	2.9E-04	kg
Surfactants	5.7E-05	lb	5.7E-05	kg
Suspended Solids	1.37	lb	1.37	kg
Thallium	1.4E-06	lb	1.4E-06	kg
Tin	2.6E-05	lb	2.6E-05	kg
Titanium	1.0E-04	lb	1.0E-04	kg
TOC	4.5E-04	lb	4.5E-04	kg
Toluene	1.6E-04	lb	1.6E-04	kg
Total biphenyls	1.4E-06	lb	1.4E-06	kg
Total dibenzothiophenes	4.3E-09	lb	4.3E-09	kg
Vanadium	7.5E-06	lb	7.5E-06	kg
Vinyl Chloride (2)	0.0000	lb	0.0000	kg
Xylene, unspecified	5.2E-05	lb	5.2E-05	kg
Yttrium	7.7E-07	lb	7.7E-07	kg
Zinc	3.4E-04	lb	3.4E-04	kg

Note: No additives or plasticizers are included in this data.

(3) This emission was provided by the Vinyl Institute based on 2003 Dioxin TRI values and listed EDC capacity for the site assuming an operating rate at EDC capacity. Molar ratios were used to convert to units for PVC. These amounts were calculated as toxic equivalent values (TEQ).

(4) This vinyl chloride emission was provided by the Vinyl Institute, based on 2003 Vinyl Chloride TRI reported values and 2003 PVC production reported by ACC Resin Statistic Report. This value was used to represent a more industry wide average value to account for facilities that did not participate in the LCI inventory. Actual reported figures were lower than the industry average.

References: Tables A-2 through A-8, A-10, and A-11.

Source: Franklin Associates, A Division of ERG models

A.2. CRUDE OIL PRODUCTION

Oil is produced by drilling into porous rock structures generally located several thousand feet underground. Once an oil deposit is located, numerous holes are drilled and lined with steel casing. Some oil is brought to the surface by natural pressure in the rock structure, although most oil requires energy to drive pumps that lift oil to the surface. Once oil is on the surface, it is separated from water and stored in tanks before being transported to a refinery. In some cases it is immediately transferred to a pipeline that transports the oil to a larger terminal.

There are two primary sources of waste from crude oil production. The first source is the "oil field brine," or water that is extracted with the oil. The brine goes through a separator at or near the well head in order to remove the oil from the water. These separators are very efficient and leave minimal oil in the water.

According to the American Petroleum Institute, 17.9 billion barrels of brine water were produced from crude oil production in 1995 (Reference A-2). This equates to a ratio of 5.4 barrels of water per barrel of oil. The majority of this brine is produced by onshore oil production facilities. Only a small percentage of onshore brine is discharged to surface water. The majority is injected into wells specifically designed for production-related waters (Reference A-3). The remaining brine is produced from offshore oil production facilities, and most of this is released to the ocean (Reference A-4). Therefore, all waterborne wastes from crude oil production are attributable to the water released from offshore production (Reference A-5). Because crude oil is frequently produced along with natural gas, a portion of the data is allocated to natural gas production (Reference A-2).

Evolving technologies are reducing the amount of brine that is extracted during oil recovery and minimizing the environmental impact of discharged brine. For example, downhole separation is a technology that separates brine from oil before bringing it to the surface; the brine is injected into subsurface injection zones. The freeze-thaw evaporation (FTE) process is another technology that reduces the discharge of brine water by using a freeze crystallization process in the winter and a natural evaporation process in the summer to extract fresh water from brine water; the fresh water can be used for horticulture or agriculture applications (Reference A-6).

There are also waterborne emissions associated with drilling wastes. Suspensions of solids, chemicals, and other materials in a base of water, oil, or synthetic-based material are referred to as drilling fluids or drilling muds. These are formulated to lubricate and cool the drill bit, carry drill cuttings from the hole to the surface, and maintain downhole hydrostatic pressure. (Reference A-7). The volume of drilling waste is small in comparison to oil field brine (Reference A-2). Less than 1% of drilling fluids from onshore production are discharged to water, while about 90% of offshore drilling fluids are discharged (References A-4 and A-8). Toxic metal pollutants are released due to the use of barite, which is employed to control the density of drilling fluids. (Reference A-7).

The primary source of atmospheric process emissions from oil extraction operations is gas produced from oil wells. The majority of this gas is recovered for sale, but some is released to the atmosphere. Atmospheric emissions from crude oil production are primarily hydrocarbons, attributed to the natural gas produced from combination wells and relate to line or transmission losses and unflared venting. Carbon dioxide is also released, primarily from storage tank venting. The amount of methane released from crude oil production was calculated from EPA's Inventory of U.S. Greenhouse Gas Emissions and Sinks, which has data specific to oil field emissions (Reference A-9).

The requirements for transporting crude oil from the production field to the Gulf Coast of the United States (where most petroleum refining in the United States occurs) were calculated from foreign and domestic supply data, port-to-port distance data, and domestic petroleum movement data (References A-10 and A-11). Based on 2001 foreign and domestic supply data, 62 percent of the United States crude oil supply is from foreign sources, 6 percent is from Alaska, and the remaining 32 percent is from the lower 48 states. These percentages were used to apportion transportation requirements among different transportation modes. With the exception of Canada, which transports crude oil to the United States by pipeline, foreign suppliers transport crude oil to the United States by ocean tanker. (In 2001, Saudi Arabia, Mexico, Canada, Venezuela, and Nigeria were the top five foreign suppliers of crude oil to the United States.) The transportation of crude oil from Alaska to the lower 48 states is also accomplished by ocean tanker. Domestic transportation of crude oil is accomplished by pipeline and barge.

Table A-2 shows the energy requirements and emissions for the extraction of crude oil.

A.3. OIL REFINING

Gasoline and diesel are the primary outputs from refineries; however, other major products include kerosene, aviation fuel, residual oil, lubricating oil, and feedstocks for the petrochemical industry. Data specific to the production of each type of refinery product are not available. Such data would be difficult to characterize because there are many types of conversion processes in oil refineries that are altered depending on market demand, quality of crude input, and other variables. Thus, the following discussion is applicable to all refinery products.

Table A-2. Data for the Extraction of Crude Oil (page 1 of 2)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Water Consumption	404	gal		3369	liter	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Petroleum	1,035	lb	18,770	1,035	kg	43.7
Total Resource			18,770			43.7
Process Energy						
Electricity (grid)	17.7	kwh	188	39.0	kwh	0.44
Natural gas	525	cu ft	588	32.8	cu meters	1.37
Distillate oil	0.15	gal	24.6	1.29	liter	0.057
Residual oil	0.10	gal	16.4	0.80	liter	0.038
Gasoline	0.082	gal	11.7	0.68	liter	0.027
Total Process			829			1.93
Environmental Emissions						
Atmospheric Emissions						
Methane	5.27	lb		5.27	kg	
Carbon Dioxide	1.11	lb		1.11	kg	
Solid Wastes						
Landfilled	26.1	lb		26.1	kg	
Waterborne Wastes						
2-Hexanone	1.4E-06	lb		1.4E-06	kg	
4-Methyl-2-Pentanone	1.9E-07	lb		1.9E-07	kg	
Acetone	4.6E-07	lb		4.6E-07	kg	
Aluminum	0.021	lb		0.021	kg	
Ammonia	0.0028	lb		0.0028	kg	
Antimony	1.3E-05	lb		1.3E-05	kg	
Arsenic, ion	4.6E-05	lb		4.6E-05	kg	
Barium	0.28	lb		0.28	kg	
Benzene	2.6E-04	lb		2.6E-04	kg	
Benzene, 1-methyl-4-(1-methylethyl)-	4.6E-09	lb		4.6E-09	kg	
Benzene, ethyl-	1.4E-05	lb		1.4E-05	kg	
Benzene, pentamethyl-	3.4E-09	lb		3.4E-09	kg	
Benzenes, alkylated, unspecified	4.3E-05	lb		4.3E-05	kg	
Benzoic acid	2.2E-04	lb		2.2E-04	kg	
Beryllium	2.9E-06	lb		2.9E-06	kg	
Biphenyl, total	2.8E-06	lb		2.8E-06	kg	
BOD5, Biological Oxygen Demand	0.025	lb		0.025	kg	
Boron	6.9E-04	lb		6.9E-04	kg	
Bromide	0.031	lb		0.031	kg	
Cadmium, ion	7.1E-06	lb		7.1E-06	kg	
Calcium, ion	0.50	lb		0.50	kg	
Chloride	6.07	lb		6.07	kg	
Chromium	5.6E-04	lb		5.6E-04	kg	
Cobalt	4.9E-06	lb		4.9E-06	kg	
COD, Chemical Oxygen Demand	0.042	lb		0.042	kg	
Copper, ion	6.2E-05	lb		6.2E-05	kg	
Cyanide	3.3E-09	lb		3.3E-09	kg	
Decane	6.4E-06	lb		6.4E-06	kg	

Table A-2. Data for the Extraction of Crude Oil (page 2 of 2)

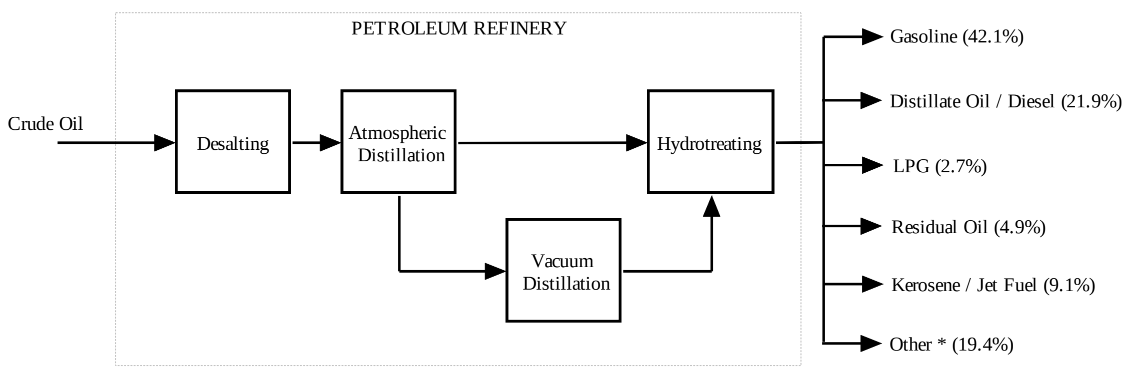
	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Dibenzofuran	8.7E-09	lb	8.7E-09	kg
Dibenzothiophene	7.0E-09	lb	7.0E-09	kg
Dibenzothiophene, total	8.6E-09	lb	8.6E-09	kg
Dissolved solids	6.47	lb	6.47	kg
Docosane	4.9E-08	lb	4.9E-08	kg
Dodecane	1.2E-05	lb	1.2E-05	kg
Eicosane	3.3E-06	lb	3.3E-06	kg
Florene, 1-methyl-	5.2E-09	lb	5.2E-09	kg
Florenes, alkylated, unspecified	2.5E-06	lb	2.5E-06	kg
Fluorine	1.2E-06	lb	1.2E-06	kg
Hexadecane	1.3E-05	lb	1.3E-05	kg
Hexanoic acid	4.7E-05	lb	4.7E-05	kg
Iron	0.039	lb	0.039	kg
Lead	1.2E-04	lb	1.2E-04	kg
Lead-210/kg	2.3E-14	lb	2.3E-14	kg
Lithium, ion	1.6E-04	lb	1.6E-04	kg
Magnesium	0.10	lb	0.10	kg
Manganese	1.5E-04	lb	1.5E-04	kg
Methane, monochloro-, R-40	1.8E-09	lb	1.8E-09	kg
Methyl ethyl ketone	3.7E-09	lb	3.7E-09	kg
Molybdenum	5.1E-06	lb	5.1E-06	kg
m-Xylene	6.3E-06	lb	6.3E-06	kg
Naphthalene	4.0E-06	lb	4.0E-06	kg
Naphthalenes, alkylated, unspecified	7.0E-07	lb	7.0E-07	kg
Napthalene, 2-methyl-	3.3E-06	lb	3.3E-06	kg
n-Hexacosane	3.0E-08	lb	3.0E-08	kg
Nickel	5.4E-05	lb	5.4E-05	kg
o-Cresol	6.4E-06	lb	6.4E-06	kg
Oils, unspecified	0.0043	lb	0.0043	kg
o-xylene	2.3E-06	lb	2.3E-06	kg
p-Cresol	6.9E-06	lb	6.9E-06	kg
Phenanthrene	1.8E-07	lb	1.8E-07	kg
Phenanthrenes, alkylated, unspecified	2.9E-07	lb	2.9E-07	kg
Phenol	7.2E-05	lb	7.2E-05	kg
Phenol, 2,4-dimethyl-	6.2E-06	lb	6.2E-06	kg
p-xylene	2.3E-06	lb	2.3E-06	kg
Radium-226/kg	8.0E-12	lb	8.0E-12	kg
Radium-228/kg	4.1E-14	lb	4.1E-14	kg
Selenium	2.5E-06	lb	2.5E-06	kg
Silver	3.1E-04	lb	3.1E-04	kg
Sodium, ion	1.48	lb	1.48	kg
Strontium	0.012	lb	0.012	kg
Sulfate	0.011	lb	0.011	kg
Sulfur	5.3E-04	lb	5.3E-04	kg
Surfactants	1.2E-04	lb	1.2E-04	kg
Suspended solids, unspecified	2.32	lb	2.32	kg
Tetradecane	5.1E-06	lb	5.1E-06	kg
Thallium	2.8E-06	lb	2.8E-06	kg
Tin	5.2E-05	lb	5.2E-05	kg
Titanium, ion	2.0E-04	lb	2.0E-04	kg
Toluene	2.4E-04	lb	2.4E-04	kg
Vanadium	5.7E-06	lb	5.7E-06	kg
Xylene	1.2E-04	lb	1.2E-04	kg
Yttrium	1.5E-06	lb	1.5E-06	kg
Zinc	4.8E-04	lb	4.8E-04	kg

References: A-2, A-4, A-7, A-8, A-9, and A-11 through A-21.

Source: Franklin Associates, A Division of ERG

A petroleum refinery processes crude oil into thousands of products using physical and/or chemical processing technology. A petroleum refinery receives crude oil, which is comprised of mixtures of many hydrocarbon compounds and uses distillation processes to separate pure product streams. Because the crude oil is contaminated (to varying degrees) with compounds of sulfur, nitrogen, oxygen, and metals, cleaning operations are common in all refineries. Also, the natural hydrocarbon components that comprise crude oil are often chemically changed to yield products for which there is higher demand. These processes, such as polymerization, alkylation, reforming, and visbreaking, are used to convert light or heavy crude oil fractions into intermediate weight products, which are more easily handled and used as fuels and/or feedstocks (Reference A-22).

This module includes data for desalting, atmospheric distillation, vacuum distillation, and hydrotreating. These are the most energy-intensive processes of a petroleum refinery, representing over 95 percent of the total energy requirements of U.S. petroleum refineries (Reference A-23). Data for cracking, reforming, and supporting processes are not available and are not included in this module. The following figure is a simplified flow diagram of the material flows and processes included in this module.



Simplified flow diagram for petroleum refinery operations for the production of fuels.
All arrows represent material flows. The percentages of refinery products represent percent by mass of total refinery output.
* "Other" category includes still gas, petroleum coke, asphalt, and petrochemical feedstocks .

Air pollution is caused by various petroleum refining processes, including vacuum distillation, catalytic cracking, thermal cracking processes, and sulfur recovery. Fugitive emissions also contribute significantly to air emissions. Fugitive emissions include leaks from valves, seals, flanges, and drains, as well as leaks escaping from storage tanks or during transfer operations. The wastewater treatment plant for a refinery is also a source of fugitive emissions (Reference A-24). Emissions of atmospheric and waterborne emissions for petroleum refineries were derived from U.S. EPA and Department of Energy publications (References A-21, A-25, A-26, A-27, and A-28).

This module expresses data on the basis 1,000 pounds of general refinery product as well as data allocated to specific refinery products. The data are allocated to specific refinery products based on the percent by mass of each product in the refinery output. The mass allocation method assigns energy requirements and environmental emissions equally to all refinery products -- equal masses of different refinery products are assigned equal energy and emissions.

Mass allocation is not the only method that can be used for assigning energy and emissions to refinery products. Heat of combustion and economic value are two additional methods for co-product allocation. Using heat of combustion of refinery products yields allocation factors similar to those derived by mass allocation, demonstrating the correlation between mass and heat of combustion. Economic allocation is complicated because market values fluctuate with supply and demand, and market data are not available for refinery products such as asphalt. This module does not apply the heat of combustion or economic allocation methods because they have no apparent advantage over mass allocation.

Co-product function expansion is yet another method for allocating environmental burdens among refinery products. Co-product function expansion is more complex than mass, heat of combustion, or economic allocation; it evaluates downstream processes and product substitutes in order to determine the percentage of total energy and emissions to assign to each refinery product. This module does not use the co-product function expansion method because it is outside the scope of this project.

There are advantages and disadvantages for each type of allocation method. Until detailed data are available for the material flows and individual processes within a refinery, life cycle practitioners will have to resort to allocation methods such as those discussed above.

The energy requirements and emissions for the refining of oil are found in Table A-3.

A.4. NATURAL GAS PRODUCTION

Natural gas is a widely used energy resource, since it is a relatively clean, efficient, and versatile fuel. The major component of natural gas is methane (CH_4). Other components of natural gas include ethane, propane, butane, and other heavier hydrocarbons, as well as water vapor, carbon dioxide, nitrogen, and hydrogen sulfides.

Natural gas is extracted from deep underground wells and is frequently co-produced with crude oil. Because of its gaseous nature, natural gas flows quite freely from wells which produce primarily natural gas, but some energy is required to pump natural gas and crude oil mixtures to the surface. An estimated 80 percent of natural gas is extracted onshore and 20 percent is extracted offshore (Reference A-15).

Table A-3. Data for the Refining of Petroleum Products

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Material Inputs						
Crude Oil	1,018	lb		1,018	kg	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	63.5	kwh	676	140	kwh	1.57
Natural gas	176	cu ft	197	11.0	cu meters	0.46
LPG	0.13	gal	14.3	1.10	liter	0.033
Residual oil	3.24	gal	555	27.0	liter	1.29
Total Process			1,442			3.36
Incoming Transportation Energy						
Barge	0.38	ton-miles		1.23	tonne-km	
Diesel	3.1E-04	gal	0.048	0.0025	liter	1.1E-04
Residual oil	0.0010	gal	0.17	0.0085	liter	4.0E-04
Ocean freighter	1,499	ton-miles		845	tonne-km	
Diesel	0.28	gal	45.2	2.38	liter	0.11
Residual	2.56	gal	440	21.4	liter	1.02
Pipeline-petroleum products	200	ton-miles		642	tonne-km	
Electricity	4.35	kwh	44.5	9.59	kwh	0.10
Total Transportation			530			1.23
Environmental Emissions						
Atmospheric Emissions						
Ammonia	0.0036	lb		0.0036	kg	
Antimony	2.0E-06	lb		2.0E-06	kg	
Arsenic	2.6E-07	lb		2.6E-07	kg	
Benzene	0.0011	lb		0.0011	kg	
Carbon dioxide, fossil	0.25	lb		0.25	kg	
Carbon monoxide	0.42	lb		0.42	kg	
Chromium	6.8E-07	lb		6.8E-07	kg	
Ethylene dibromide	4.3E-06	lb		4.3E-06	kg	
Methane, chlorotrifluoro-, CFC-13	2.2E-05	lb		2.2E-05	kg	
Methane, fossil	0.037	lb		0.037	kg	
Methane, tetrachloro-, CFC-10	1.4E-06	lb		1.4E-06	kg	
Nickel	5.8E-06	lb		5.8E-06	kg	
Nitrogen oxides	0.42	lb		0.42	kg	
NMVOC, non-methane volatile organic compounds, unspecified origin	0.68	lb		0.68	kg	
Particulates, < 10 um	0.031	lb		0.031	kg	
Particulates, < 2.5 um	0.023	lb		0.023	kg	
Polycyclic organic matter, unspecified	5.6E-05	lb		5.6E-05	kg	
SO2	0.25	lb		0.25	kg	
Solid Wastes						
Landfilled	5.60	lb		5.60	kg	
Waterborne Emissions						
Ammonia	0.015	lb		0.015	kg	
BOD5, Biological Oxygen Demand	0.034	lb		0.034	kg	
Chromium	3.0E-06	lb		3.0E-06	kg	
COD, Chemical Oxygen Demand	0.23	lb		0.23	kg	
Lead	9.8E-07	lb		9.8E-07	kg	
Mercury	6.0E-08	lb		6.0E-08	kg	
Oils, unspecified	0.011	lb		0.011	kg	
Phenol	2.3E-04	lb		2.3E-04	kg	
Selenium	1.6E-06	lb		1.6E-06	kg	
Sulfide	1.9E-04	lb		1.9E-04	kg	
Suspended solids, unspecified	0.028	lb		0.028	kg	
Vanadium	5.4E-05	lb		5.4E-05	kg	

References: A-9, A-19, A-20, and A-29 through A-33

Source: Franklin Associates, A Division of ERG

Atmospheric emissions from natural gas production result primarily from unflared venting. Methane and non-combustion carbon dioxide emissions from natural gas extraction are generally process related, with the largest source of these emissions from normal operations, system upsets, and routine maintenance. Waterborne wastes result from brines that occur when natural gas is produced in combination with oil. In cases where data represent both crude oil and natural gas extraction, the data module allocates environmental emissions based on the percent weight of natural gas produced. The data module also apportions environmental emissions according to the percent share of onshore and offshore extraction.

Energy data for natural gas production were calculated from fuel consumption data for the crude oil and natural gas extraction industry (Reference A-34). The energy and emissions data for the production of natural gas is displayed in Table A-4.

A.5. NATURAL GAS PROCESSING

Once raw natural gas is extracted, it is processed to yield a marketable product. First, the heavier hydrocarbons such as ethane, butane and propane are removed and marketed as liquefied petroleum gas (LPG). Then the water vapor, carbon dioxide, and nitrogen are removed to increase the quality and heating value of the natural gas. If the natural gas has a high hydrogen sulfide content, it is considered “sour.” Before it is used, hydrogen sulfide is removed by adsorption in an amine solution—a process known as “sweetening.”

Atmospheric emissions result from acid gas removal processes and flaring of hydrogen sulfide (H2S), the regeneration of glycol solutions, and fugitive emissions of methane. Methane and carbon dioxide emissions from natural gas processing were calculated based on emissions reported in the U.S. Greenhouse Gas Inventory. For natural gas that is sweetened, the majority of the H_2S removed is used for production of sulfur (Reference A-35). Sulfur dioxide emissions were calculated for flaring of H_2S that is not used for recovered sulfur production (Reference A-36). . Glycol solutions are used to dehydrate natural gas, and the regeneration of these solutions result in the release of BTEX (benzene, toluene, ethylbenzene, and xylene) as well as a variety of less toxic organics (Reference A-37, A-38). Negligible particulate emissions are produced from natural gas plants, and the relatively low processing temperatures (<1,200 degrees Fahrenheit) prevent the formation of nitrogen oxides (NOx).

Natural gas is transported primarily by pipeline, but a small percentage is compressed and transported by insulated railcars and tankers (References A-39 and A-40). Transportation data were calculated from the net annual quantities of natural gas imported and exported by each state (Reference A-41).

Energy data for natural gas processing were calculated from fuel consumption data for the natural gas liquids extraction industry (Reference A-12). Table A-5 shows the energy and emissions data for processing natural gas. Sulfur was given no coproduct allocation in this process. The amount of H_2S in the sour natural gas varies widely depending on where it is extracted.

Table A-4. Data for the Extraction of Natural Gas (page 1 of 2)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Energy of Material Resource						
Natural Gas	1,038	lb	21,416	1,038	kg	49.8
Total Resource			21,416			49.8
Process Energy						
Electricity (grid)	17.7	kwh	188	39.0	kwh	0.44
Natural gas	525	cu ft	588	32.8	cu meters	1.37
Distillate oil	0.15	gal	24.6	1.29	liter	0.057
Residual oil	0.10	gal	16.4	0.8	liter	0.038
Gasoline	0.082	gal	11.7	0.68	liter	0.027
Total Process			829			1.93
Environmental Emissions						
Atmospheric Emissions						
Methane	3.40	lb		3.40	kg	
Carbon dioxide (fossil)	17.0	lb		17.0	kg	
Solid Wastes						
Landfilled	26.1	lb		26.1	kg	
Waterborne Wastes						
2-Hexanone	1.7E-06	lb		1.7E-06	kg	
4-Methyl-2-Pentanone	7.4E-07	lb		7.4E-07	kg	
Acetone	1.8E-06	lb		1.8E-06	kg	
Aluminum	0.023	lb		0.023	kg	
Ammonia	0.0025	lb		0.0025	kg	
Antimony	1.4E-05	lb		1.4E-05	kg	
Arsenic, ion	4.7E-05	lb		4.7E-05	kg	
Barium	0.31	lb		0.31	kg	
Benzene	2.6E-04	lb		2.6E-04	kg	
Benzene, 1-methyl-4-(1-methylethyl)-	1.8E-08	lb		1.8E-08	kg	
Benzene, ethyl-	1.5E-05	lb		1.5E-05	kg	
Benzene, pentamethyl-	1.3E-08	lb		1.3E-08	kg	
Benzenes, alkylated, unspecified	4.7E-05	lb		4.7E-05	kg	
Benzoic acid	2.6E-04	lb		2.6E-04	kg	
Beryllium	3.0E-06	lb		3.0E-06	kg	
Biphenyl	3.1E-06	lb		3.1E-06	kg	
BOD5, Biological Oxygen Demand	0.024	lb		0.024	kg	
Boron	8.0E-04	lb		8.0E-04	kg	
Bromide	0.030	lb		0.030	kg	
Cadmium, ion	7.3E-06	lb		7.3E-06	kg	
Calcium, ion	0.50	lb		0.50	kg	
Chloride	6.30	lb		6.30	kg	
Chromium	6.2E-04	lb		6.2E-04	kg	
Cobalt	5.6E-06	lb		5.6E-06	kg	
COD, Chemical Oxygen Demand	0.040	lb		0.040	kg	
Copper, ion	6.7E-05	lb		6.7E-05	kg	
Cyanide	1.3E-08	lb		1.3E-08	kg	
Decane	7.4E-06	lb		7.4E-06	kg	
Dibenzofuran	3.3E-08	lb		3.3E-08	kg	
Dibenzothiophene	2.7E-08	lb		2.7E-08	kg	
Dibenzothiophene, total	9.4E-09	lb		9.4E-09	kg	
Dissolved solids	6.23	lb		6.23	kg	
Docosane	1.9E-07	lb		1.9E-07	kg	
Dodecane	1.4E-05	lb		1.4E-05	kg	

Table A-4. Data for the Extraction of Natural Gas (page 2 of 2)

	English units (Basis: 1,000 lb)		SI units (Basis: 1,000 kg)	
Eicosane	3.9E-06	lb	3.9E-06	kg
Florene, 1-methyl-	2.0E-08	lb	2.0E-08	kg
Florenes, alkylated, unspecified	2.7E-06	lb	2.7E-06	kg
Fluorine	1.3E-06	lb	1.3E-06	kg
Hexadecane	1.5E-05	lb	1.5E-05	kg
Hexanoic acid	5.3E-05	lb	5.3E-05	kg
Iron	0.043	lb	0.043	kg
Lead	1.3E-04	lb	1.3E-04	kg
Lead-210/kg	2.6E-14	lb	2.6E-14	kg
Lithium, ion	0.15	lb	0.15	kg
Magnesium	0.10	lb	0.10	kg
Manganese	1.4E-04	lb	1.4E-04	kg
Methane, monochloro-, R-40	7.1E-09	lb	7.1E-09	kg
Methyl ethyl ketone	1.4E-08	lb	1.4E-08	kg
Molybdenum	5.8E-06	lb	5.8E-06	kg
m-Xylene	7.5E-06	lb	7.5E-06	kg
Naphthalene	4.6E-06	lb	4.6E-06	kg
Naphthalenes, alkylated, unspecified	7.7E-07	lb	7.7E-07	kg
Napthalene, 2-methyl-	3.9E-06	lb	3.9E-06	kg
n-Hexacosane	1.2E-07	lb	1.2E-07	kg
Nickel	5.8E-05	lb	5.8E-05	kg
o-Cresol	7.3E-06	lb	7.3E-06	kg
Oils, unspecified	0.0045	lb	0.0045	kg
o-xylene	2.8E-06	lb	2.8E-06	kg
p-Cresol	7.9E-06	lb	7.9E-06	kg
Phenanthrene	2.0E-07	lb	2.0E-07	kg
Phenanthrenes, alkylated, unspecified	3.2E-07	lb	3.2E-07	kg
Phenols, unspecified	7.4E-05	lb	7.4E-05	kg
Phenol, 2,4-dimethyl-	7.1E-06	lb	7.1E-06	kg
p-xylene	2.8E-06	lb	2.8E-06	kg
Radium-226/kg	9.2E-12	lb	9.2E-12	kg
Radium-228/kg	4.7E-14	lb	4.7E-14	kg
Selenium	2.8E-06	lb	2.8E-06	kg
Silver	3.0E-04	lb	3.0E-04	kg
Sodium, ion	1.43	lb	1.43	kg
Strontium	0.014	lb	0.014	kg
Sulfate	0.010	lb	0.010	kg
Sulfur	6.5E-04	lb	6.5E-04	kg
Surfactants, unspecified	1.2E-04	lb	1.2E-04	kg
Suspended solids, unspecified	2.56	lb	2.56	kg
Tetradecane	6.0E-06	lb	6.0E-06	kg
Thallium	3.1E-06	lb	3.1E-06	kg
Tin	5.8E-05	lb	5.8E-05	kg
Titanium, ion	2.2E-04	lb	2.2E-04	kg
Toluene	2.4E-04	lb	2.4E-04	kg
Vanadium	6.8E-06	lb	6.8E-06	kg
Xylene	1.1E-04	lb	1.1E-04	kg
Yttrium	1.7E-06	lb	1.7E-06	kg
Zinc	5.3E-04	lb	5.3E-04	kg

References: A-2, A-4, A-7, A-8, A-9, and A-11 through A-21

Source: Franklin Associates, A Division of ERG

Table A-5. Data for the Processing of Natural Gas

	English units (Basis: 1,000 lb)		Total Energy Thousand Btu	SI units (Basis: 1,000 kg)		Total Energy GigaJoules
Material Inputs						
Natural gas	1,005	lb		1,005	kg	
Energy Usage						
Process Energy						
Electricity (grid)	9.67	kwh	103	21.3	kwh	0.24
Natural gas	554	cu ft	620	34.6	cu meters	1.44
Distillate oil	0.0060	gal	0.96	0.050	liter	0.0022
Residual oil	0.0059	gal	1.02	0.050	liter	0.0024
Gasoline	0.0057	gal	0.81	0.048	liter	0.0019
Total Process			726			1.69
Environmental Emissions						
Atmospheric Emissions						
BTEX	0.34	lb		0.34	kg	
Benzene	0.096	lb		0.096	kg	
Toluene	0.15	lb		0.15	kg	
Ethylbenzene	0.012	lb		0.012	kg	
Xylene	0.087	lb		0.087	kg	
Methane	1.88	lb		1.88	kg	
SO2	1.90	lb		1.90	kg	
VOC	0.77	lb		0.77	kg	
Carbon Dioxide	53.0	lb		53.0	kg	

References:A-15 through A-18, A-24, A-33, A-37, A-39, A-40, A-42, A-43, and A-44.

Source: Franklin Associates, A Division of ERG

A.6. OLEFINS PRODUCTION (ETHYLENE)

The primary process used for manufacturing olefins is the thermal cracking of saturated hydrocarbons such as ethane, propane, naphtha, and other gas oils.

Typical production of ethylene, propylene, and other coproducts begins when hydrocarbons and steam are fed to the cracking furnace. After being heated to temperatures around 1,000° Celsius, the cracked products are quenched in heat exchangers which produce high pressure steam. Fuel oil is separated from the main gas stream in a multi-stage centrifugal compressor. The main gas stream then undergoes hydrogen sulfide removal and drying. The final step involves fractional distillation of the various reaction products.

Within the hydrocracker, an offgas is produced from the raw materials entering. A portion of this offgas is used within the hydrocracker to produce steam, while the remaining portion is exported from the hydrocracker as a coproduct, as discussed below. The offgas used within the hydrocracker is shown in Table A-6 as “Internal offgas use.” This offgas is shown as a weight of natural gas and petroleum input to produce the energy, as well as the energy amount produced from those weights.

Data was collected from individual plants, and a mass allocation was used to provide an output of 1,000 pounds/kilograms of olefin product. Then a weighted average using ethylene production amounts for each plant was applied to the individual olefins plant production data collected from three leading producers (8 thermal cracking units) in North America. Transportation amounts for ethylene were calculated using a weighted average of data collected from the polyethylene producers. Numerous coproduct streams are produced during this process. Fuel gas and off-gas were two of the coproducts produced that were exported to another process for fuel use. When these fuel coproducts are exported from the hydrocracker, they carry with them the allocated share of the inputs and outputs for their production. The ratio of the mass of the exported fuel over the total mass output was removed from the total inputs and outputs of the hydrocracker, and the remaining inputs and outputs are allocated over the material hydrocracker products (Equation 1).

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

where
IO = Input/Output Matrix to produce all products/coproducts
M_{EO} = Mass of Exported Offgas
M_{Total} = Mass of all Products and Coproducts (including fuels)

No energy credit is applied for the exported fuels, since both the inputs and outputs for the exported fuels have been removed from the data set. Table A-6 shows the averaged energy and emissions data for the production of ethylene.

As of 2003, there were 16 olefin producers and at least 29 olefin plants in the U.S. (Reference A-45). While data was collected from a relatively small sample of plants, the olefins producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American olefins production. All data collected were individually reviewed by the data providers.

To assess the quality of the data collected for olefins, the collection method, technology, industry representation, time period, and geography were considered. The data collection methods for olefins include direct measurements, information provided by purchasing and utility records, and estimates. The standard production technology for olefins is the steam cracking of hydrocarbons (including natural gas liquids and petroleum liquids). The data in this module represent steam cracking of natural gas and petroleum. All data submitted for olefins represent the year 2003 and U.S. and Canada production.

A.7. SALT 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. Vacuum pan salt and solar salt represent a small portion of U.S. production and are thus not included in this data module. This data module represents a mix of underground mining and solution mining techniques.

Approximately 95 percent of salt-based chlorine and caustic facilities use brine salt. In solution mining, pressurized fresh water is introduced to the bedded salt through an injection well. The brine is then pumped to the surface for treatment.

Approximately 5 percent of salt-based chlorine and caustic facilities use rock salt. Rock salt mining uses the room and pillar method. The room and pillar method excavates a series of rectangular sections, leaving columns of undisturbed salt in order to support the mine roof. After rock salt is crushed in the mine, it is transported by conveyor belts to the surface. On the surface, the rock salt is screened and prepared for shipment.

No data are available for the energy requirements of the solution mining of salt brine in the U.S. Energy data for the mining/extracting and purification of the salt in this analysis come from the Eco-profile of purified brine commissioned by PlasticsEurope. The transportation data was estimated from chlorine data collected from a confidential source.

No U.S. data are available for air emissions from salt mining. Since salt mining involves no chemical reactions and minimal processing requirements, it is assumed that negligible process emissions result from salt mining. Total suspended solids (TSS) are the only BPT limited water effluent from sodium chloride production (Reference A-47). No data are available for other water effluents. However, 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 (Reference A-48). Salt deposits are relatively pure and require minimal beneficiation (Reference A-49). Any overburden that may be removed during rock salt mining can be returned to the mining site after the salt is recovered. Similarly, solution mining is a technology that does not generate significant amounts of solid wastes. It is thus assumed that salt mining produces negligible quantities of solid waste.

Table A-7 displays the energy requirements for the mining/extraction and purification of salt.

Table A-6. Data for the Production of Ethylene

	English units (Basis: 1,000 lb)			Total Energy Thousand Btu	SI units (Basis: 1,000 kg)		Total Energy GigaJoules
Material Inputs (1)							
Refined Petroleum Products	186	lb			186	kg	
Processed Natural Gas	830	lb			830	kg	
Water Consumption	195	gal			1,627	liter	
Energy Usage							
Process Energy							
Electricity (grid)	35.7	kwh		380	78.8	kwh	0.88
Electricity (cogeneration)	202	cu ft	(3)	227	12.6	cu meters	0.53
Natural Gas	2,272	cu ft		2,545	142	cu meters	5.92
Gasoline	0.011	gal		1.56	0.091	liter	0.0036
Diesel	0.0095	gal		1.51	0.079	liter	0.0035
Internal Offgas use (2)							
From Oil	26.1	lb		800	26.1	kg	1.86
From Natural Gas	119	lb		3,645	119	kg	8.49
Recovered Energy	12.4	thousand Btu		12.4	29	MJ	0.029
Total Process				7,587			17.7
Incoming Transportation Energy							
Combination truck	7.64	ton-miles			4.31	tonne-km	
Diesel	0.080	gal		12.7	0.67	liter	0.030
Rail	6.59	ton-miles			3.72	tonne-km	
Diesel	0.016	gal		2.60	0.14	liter	0.0060
Barge	15.6	ton-miles			8.82	tonne-km	
Diesel	0.013	gal		1.99	0.10	liter	0.0046
Residual oil	0.042	gal		7.14	0.35	liter	0.017
Pipeline-natural gas	475	ton-miles			268	tonne-km	
Natural gas	327	cu ft		367	20.4	cu meter	0.85
Pipeline-Petroleum Products	22.7	ton-miles			73.2	tonne-km	
Electricity	0.50	kwh		5.08	1.09	kwh	0.012
Total Transportation				396			0.92
Environmental Emissions							
Atmospheric Emissions - Process							
Carbon Monoxide	0.0010	lb	(4)		0.0010	kg	
Chlorine	1.0E-04	lb	(4)		1.0E-04	kg	
HCFC-022	1.0E-06	lb	(4)		1.0E-06	kg	
Hydrogen Chloride	1.0E-06	lb	(4)		1.0E-06	kg	
Hydrogen	0.0040	lb			0.0040	kg	
Hydrocarbons (NM)	0.091	lb			0.091	kg	
Methane	0.0010	lb	(4)		0.0010	kg	
Other Organics	0.0010	lb	(4)		0.0010	kg	
Particulates (unspecified)	0.0084	lb			0.0084	kg	
Particulates (PM10)	0.10	lb	(4)		0.10	kg	
Sulfur Oxides	0.0041	lb			0.0041	kg	
VOC	0.010	lb	(4)		0.010	kg	
Atmospheric Emissions - Fuel-Related (5)							
Carbon Dioxide (fossil)	648	lb			648	kg	
Carbon Monoxide	0.39	lb			0.39	kg	
Nitrogen Oxides	0.60	lb			0.60	kg	
PM 2.5	0.0093	lb			0.0093	kg	
Sulfur Oxides	0.059	lb			0.059	kg	
Solid Wastes							
Landfilled	0.28	lb			0.28	kg	
Burned	3.62	lb			3.62	kg	
Waste-to-Energy	0.023	lb			0.023	kg	
Waterborne Wastes							
Acetone	1.0E-08	lb	(4)		1.0E-08	kg	
Benzene	1.0E-05	lb	(4)		1.0E-05	kg	
BOD	6.7E-04	lb			6.7E-04	kg	
COD	0.010	lb	(4)		0.010	kg	
Ethylbenzene	1.0E-05	lb	(4)		1.0E-05	kg	
Naphthalene	1.0E-08	lb	(4)		1.0E-08	kg	
Phenol	0.0010	lb	(4)		0.0010	kg	
Styrene	1.0E-06	lb	(4)		1.0E-06	kg	
Suspended Solids	0.0045	lb			0.0045	kg	
Toluene	1.0E-04	lb	(4)		1.0E-04	kg	
Total Organic Carbon	0.0010	lb	(4)		0.0010	kg	
Xylene	1.0E-06	lb	(4)		1.0E-06	kg	

(1) Specific input materials from oil refining and natural gas processing include ethane, propane, liquid feed, heavy raffinate, and DNG.

(2) A portion of the material feed combusts within the hydrocracker and produces an offgas, which provides an internal energy source

(3) The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency.

(4) This emission was 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.

(5) These fuel-related emissions were provided by the plants. These take into account the combustion of the off gas, as well as the natural gas.

References: A-46

Source: Franklin Associates, A Division of ERG

Table A-7. Data for the Mining of Salt

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	15.1	kwh	155	33.3	kwh	0.36
Natural gas	397	cu ft	445	24.8	cu meters	1.04
Bit./Sbit. Coal	11.7	lb	131	11.7	kg	0.31
Distillate oil	1.21	gal	192	10.1	liter	0.45
Total Process			924			2.15

References: A-50 through A-52

Source: Franklin Associates, A Division of ERG

A.8. CHLORINE OR SODIUM HYDROXIDE PRODUCTION

Chlorine and caustic soda (sodium hydroxide) are produced from salt by an electrolytic process. The aqueous sodium chloride solution is electrolyzed to produce caustic soda, chlorine, and hydrogen gas.

There are three commercial processes for the electrolysis of sodium chloride: (1) the diaphragm cell process, (2) the mercury cathode cell process, and (3) the membrane cell process. Diaphragm cell electrolysis is used for 67 percent of production, mercury cathode cell electrolysis is used for 3.5 percent of production, and membrane cell electrolysis is used for 29.5 percent of production (Reference A-61). Membrane cell electrolysis is the most recent of these technologies and is gradually gaining commercial acceptance. Membrane cell electrolysis has relatively low energy requirements, but its high capital costs have hindered its growth (Reference A-53). Limited data are available for membrane cell electrolysis; this data module thus assigns 96.5 percent of chlorine and caustic soda production to diaphragm/membrane cell electrolysis and 3.5 percent of chlorine and caustic soda production to mercury cathode cell electrolysis (Reference A-61). The mercury cell technology is more likely to be used to produce high-purity caustic; no longer is the chlorine used in EDC coming from mercury cells (Reference A-54).

The diaphragm cell uses graphite anodes and steel cathodes. Brine solution is passed through the anode compartment of the cell, where the salt is decomposed into chlorine gas and sodium ions. The gas is removed through a pipe at the top of the cell. The sodium ions pass through a cation-selective diaphragm. The depleted brine is either resaturated with salt or concentrated by evaporation and recycled to the cell. The sodium ions transferred across the diaphragm react with water at the cathode to produce hydrogen and sodium hydroxide. Diffusion of the cathode products back into the brine solution is prevented by the diaphragm.

The mercury cell uses graphite anodes and mercury cathodes. Sodium reacts with the mercury cathode to produce an amalgam (an alloy of mercury and sodium) that is sent to another compartment of the cell and reacted with water to produce hydrogen and high purity sodium hydroxide. The chemistry that occurs at the mercury cathode includes the following reactions:

$NaCl + xHg \rightarrow 1/2\ Cl_2 + Na(Hg)x$ and
$Na(Hg)x + H_2O \rightarrow NaOH + 1/2H_2 + xHg$

Mercury loss is a disadvantage of the mercury cathode cell process. Some of the routes by which mercury can escape are in the hydrogen gas stream, in cell room ventilation air and washing water, through purging of the brine loop and disposal of brine sludges, and through end box fumes.

Titanium anodes, coated with metal oxide finishes, are gaining commercial acceptance and are gradually replacing graphite anodes. The advantages of titanium anodes are (1) corrosion resistance and (2) the low activation energy for electrolysis at the anode surface (Reference A-55).

The reason coproduct credit was given is that it is not possible, using the electrolytic cell, to get chlorine from salt without also producing sodium hydroxide and hydrogen, both of which have commercial value as useful coproducts. Likewise, sodium hydroxide cannot be obtained without producing the valuable coproducts of chlorine and hydrogen. Furthermore, it is not possible to control the cell to increase or decrease the amount of chlorine or caustic soda resulting from a given input of salt. This is determined by the stoichiometry of the reaction; the electrolysis of sodium chloride produces approximately 1.1 tons caustic soda per ton of chlorine. Caustic soda is usually handled and sold as a 50% solution in water.

The energy requirements and environmental emissions for the production of chlorine are given in Table A-8 and Table A-9. Table A-9 also provides the dataset for the coproduct, sodium hydroxide, which is the same data when using mass allocation. Diaphragm and mercury cells are considered as the main source of chlorine/caustic in this analysis. Data was collected from one plant that used both the diaphragm and membrane technologies, and so their dataset represented both cells. According to discussions with The Vinyl Institute, no chlorine produced from mercury cell technology is going into EDC production as of 2012. None of the chlorine used by EDC plants is assumed to come from the mercury cell technology as shown in Table A-8. For the overall chlorine/caustic industry, it is estimated that 96.5 percent of the cell technology is diaphragm and membrane, while 3.5 percent of the cell technology is mercury. The collected datasets were weighted using these fractions in Table A-9.

As of 2003 there were 20 chlorine/caustic producers and 41 chlorine/caustic plants in the U.S. for the three standard technologies (Reference A-52). The chlorine/caustic data collected for this module represent 1 producer and 3 plants in the U.S. Besides this recently collected data, 2 diaphragm cell datasets and 2 mercury cell datasets were used from the early 1990s. While data was collected from a small sample of plants, the chlorine/caustic producer who provided data for this module verified that the characteristics of their plant are representative of the diaphragm/membrane cell technology for North American chlorine/caustic production. The average dataset was reviewed and accepted by the chlorine/caustic data provider.

One of the five company datasets was collected for this project and represents 2003 data, while the other four datasets comes from 1989-1992. The 2003 data were collected from direct measurements, calculated from equipment specifications, taken from purchasing/utility records, and engineering estimates. The collection methods for the older data are unknown.

A.9. ETHYLENE DICHLORIDE (EDC) PRODUCTION

Ethylene dichloride is produced from the reaction of ethylene and chlorine. Ethylene is chlorinated in the liquid phase at a temperature of 20° to 120° C and a pressure of 75 psi. A ferric chloride catalyst is used to drive the reaction. The crude product from the reactor is then purified by distillation to yield ethylene dichloride. Ethylene dichloride data was collected with VCM data and are included within the VCM dataset (Table A-10).

A.10. VINYL CHLORIDE MONOMER (VCM) PRODUCTION

Vinyl chloride monomer (VCM) is produced almost exclusively by thermal cleavage (dehydrochlorination) of ethylene dichloride. The ethylene dichloride is fed to the cracking unit to form VCM and HCl. The HCl from this process is fed back to the ethylene dichloride reaction. In the case of the collected EDC/VCM data, either the producer used all HCl produced or not enough HCl was produced and supplemental HCl was purchased. Unreacted ethylene dichloride is separated from the VCM.

Data for the production of EDC/VCM were provided by three leading producers (3 plants) in North America to Franklin Associates under contract to Plastics Division of the American Chemistry Council (ACC). The energy requirements and environmental emissions for the production of EDC/VCM are shown in Table A-10. Dichloroethane is produced as a coproduct during this process. A mass basis was used to partition the credit for this coproduct.

As of 2003 there were 8 VCM producers and 12 VCM plants in the U.S. (Reference A-59). While data was collected from a small sample of plants, the EDC/VCM producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American EDC/VCM production. The average dataset was reviewed and accepted by all EDC/VCM data providers.

Table A-8. Data for the Production of Chlorine Specific to PVC (100% Diaphragm/Membrane)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Salt	894	lb		894	kg	
Water Consumption	412	gal		3,436	liter	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	272	kwh	2,795	599	kwh	6.51
Electricity (cogeneration)	172	kwh	1,175	380	kwh	2.74
Natural gas	1,969	cu ft	2,206	123	cu meters	5.13
Bit./Sbit. Coal	25.7	lb	289	25.7	kg	0.67
Residual oil	0.038	gal	6.53	0.32	liter	0.015
Total Process			6,471			15.1
Incoming Transportation Energy						
Rail	1.12	ton-miles		3.60	tonne-km	
Diesel	0.0028	gal	0.44	0.023	liter	0.0010
Barge	1.12	ton-miles		3.60	tonne-km	
Diesel	8.9E-04	gal	0.14	0.0075	liter	3.3E-04
Residual oil	0.0030	gal	0.51	0.025	liter	0.0012
Pipeline-petroleum products	103	ton-miles		330.00	tonne-km	
Electricity	2.24	kwh	22.9	4.93	kwh	0.053
Total Transportation			24.0			0.056
Environmental Emissions						
Atmospheric Emissions						
Benzene	2.3E-05	lb		2.3E-05	kg	
Carbon Dioxide (fossil)	0.075	lb		0.075	kg	
Carbon Monoxide	1.4E-04	lb		1.4E-04	kg	
Carbon Tetrachloride	1.9E-04	lb		1.9E-04	kg	
Chlorine	0.0011	lb		0.0011	kg	
HCFC-123	9.1E-05	lb		9.1E-05	kg	
HFC-134a	9.1E-05	lb		9.1E-05	kg	
NM Hydrocarbons	2.7E-04	lb		2.7E-04	kg	
Hydrogen Chloride	3.3E-04	lb		3.3E-04	kg	
Lead	1.1E-08	lb		1.1E-08	kg	
Methane	1.1E-06	lb		1.1E-06	kg	
Nitrogen Oxides	0.0039	lb		0.0039	kg	
Other Organics	8.1E-06	lb		8.1E-06	kg	
Particulates	0.0028	lb		0.0028	kg	
PM2.5	1.2E-04	lb		1.2E-04	kg	
PM10	0.021	lb		0.021	kg	
Sulfur Oxides	5.5E-04	lb		5.5E-04	kg	
Solid Wastes						
Landfilled	0.51	lb		0.51	kg	
Burned	1.44	lb		1.44	kg	
Waterborne Wastes						
BOD	0.27	lb		0.27	kg	
Copper	1.2E-07	lb		1.2E-07	kg	
Dissolved Solids	44.9	lb		44.9	kg	
Nickel	5.9E-07	lb		5.9E-07	kg	
Suspended Solids	0.081	lb		0.081	kg	

Note: According to the Vinyl Institute, EDC producers no longer purchase chlorine produced using the mercury cell technology.

References:A-51, A-54, A-56, A-57, and A-59

Source: Franklin Associates, A Division of ERG

Table A-9. Data for the Production of Sodium Hydroxide or Chlorine (96.5% Diaphragm/Membrane and 3.5% Mercury)

	English units (Basis: 1,000 lb)			SI units (Basis: 1,000 kg)		
Raw Materials						
Salt	890	lb		890	kg	
Water Consumption	401	gal		3,342	liter	
Energy Usage			**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy						
Electricity (grid)	286	kwh	2,938	629	kwh	6.84
Electricity (cogeneration)	166	kwh	1,134	366	kwh	2.64
Natural gas	1,909	cu ft	2,138	119	cu meters	4.98
Bit./Sbit. Coal	25.4	lb	285	25.4	kg	0.66
Residual oil	0.083	gal	14.3	0.69	liter	0.033
Total Process			6,511			15.2
Incoming Transportation Energy						
Rail	1.12	ton-miles		3.60	tonne-km	
Diesel	0.0028	gal	0.44	0.023	liter	1.0E-03
Barge	1.12	ton-miles		0.63	tonne-km	
Diesel	8.9E-04	gal	0.14	0.0075	liter	3.3E-04
Residual oil	0.0030	gal	0.51	0.025	liter	0.0012
Pipeline-petroleum products	103	ton-miles		330	tonne-km	
Electricity	2.24	kwh	22.9	4.93	kwh	0.053
Total Transportation			22.9			0.053
Environmental Emissions						
Atmospheric Emissions						
Benzene	2.2E-05	lb		2.2E-05	kg	
Carbon Dioxide (fossil)	0.073	lb		0.073	kg	
Carbon Monoxide	1.3E-04	lb		1.3E-04	kg	
Carbon Tetrachloride	1.9E-04	lb		1.9E-04	kg	
Chlorine	0.0011	lb		0.0011	kg	
HCFC-123	8.8E-05	lb		8.8E-05	kg	
HFC-134a	8.8E-05	lb		8.8E-05	kg	
NM Hydrocarbons	2.6E-04	lb		2.6E-04	kg	
Hydrogen Chloride	3.1E-04	lb		3.1E-04	kg	
Lead	1.1E-08	lb		1.1E-08	kg	
Mercury	6.5E-05	lb		6.5E-05	kg	
Methane	1.0E-06	lb		1.0E-06	kg	
Nitrogen Oxides	0.0037	lb		0.0037	kg	
Other Organics	7.8E-06	lb		7.8E-06	kg	
Particulates	0.0027	lb		0.0027	kg	
PM2.5	1.2E-04	lb		1.2E-04	kg	
PM10	0.021	lb		0.021	kg	
Sulfur Oxides	5.3E-04	lb		5.3E-04	kg	
Solid Wastes						
Landfilled	0.79	lb		0.79	kg	
Burned	1.39	lb		1.39	kg	
Waterborne Wastes						
BOD	0.26	lb		0.26	kg	
Copper	1.2E-07	lb		1.2E-07	kg	
Dissolved Solids	43.3	lb		43.3	kg	
Mercury	1.5E-07	lb		1.5E-07	kg	
Nickel	5.7E-07	lb		5.7E-07	kg	
Sulfides	1.8E-05	lb		1.8E-05	kg	
Suspended Solids	0.078	lb		0.078	kg	

References: A-51, A-54, A-56, A-57, and A-61

Source: Franklin Associates, A Division of ERG

Table A-10. Data for the Production of Ethylene Dichloride (EDC)/Vinyl Chloride Monomer (VCM)

	English units (Basis: 1,000 lb)				SI units (Basis: 1,000 kg)		
Material Inputs							
Ethylene	450	lb			450	kg	
Chlorine	540	lb			540	kg	
Oxygen	140	lb			140	kg	
Water Consumption	104	gal			870	liter	
Energy Usage				**Total Energy Thousand Btu**			**Total Energy GigaJoules**
Process Energy							
Electricity (grid)	68.0	kwh		700	150	kwh	1.63
Electricity (cogeneration)	325	cu ft	(1)	364	20.3	cu meters	0.85
Natural gas	2,082	cu ft		2,332	130	cu meters	5.43
Total Process				3,396			7.91
Incoming Transportation Energy							
Combination truck	13.2	ton-miles			42.4	tonne-km	
Diesel	0.14	gal		22.0	1.15	liter	0.051
Rail	34.2	ton-miles			110	tonne-km	
Diesel	0.085	gal		13.5	0.71	liter	0.031
Pipeline-natural gas	0.071	ton-miles			0.23	tonne-km	
Natural gas	0.049	cu ft		0.055	0.0031	cu meter	1.3E-04
Pipeline-petroleum products	28.6	ton-miles			92.0	tonne-km	
Electricity	0.62	kwh		6.38	1.37	kwh	0.015
Total Transportation				41.9			0.097
Environmental Emissions							
Atmospheric Emissions							
Carbon Monoxide	0.011	lb			0.011	kg	
Carbon Dioxide	37.3	lb			37.3	kg	
Chlorine	0.0010	lb	(2)		0.0010	kg	
Hydrochloric Acid	0.0026	lb			0.0026	kg	
Nitrogen Oxides	0.032	lb			0.032	kg	
Other Organics	0.0069	lb	(3)		0.0069	kg	
Particulates (unknown)	0.010	lb	(2)		0.010	kg	
PM2.5	0.0010	lb	(2)		0.0010	kg	
PM10	0.0010	lb	(2)		0.0010	kg	
Solid Wastes							
Landfilled	1.0E-05	lb			1.0E-05	kg	
Burned	1.0E-07	lb			1.0E-07	kg	
Waste-to-Energy	4.3E-06	lb			4.3E-06	kg	
Waterborne Wastes							
Chlorides	1.0E-05	lb	(2)		1.0E-05	kg	
Copper	1.0E-07	lb	(2)		1.0E-07	kg	
Vinyl Chloride	4.3E-06	lb	(4)		4.3E-06	kg	

(1) The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency.
(2) This emission was 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.
(3) This category contains small amounts of EDC and VCM as well as other hydrocarbons which were not separated out by the data providers. These amounts may be overcounting the VCM emissions as the Vinyl Institute provided atmospheric VCM emissions for the production of EDC/VCM/PVC as shown in Table A-11.
(4) This vinyl chloride emission was provided by the Vinyl Institute, based on 2011 Vinyl Chloride TRI reported values and 2011 PVC production reported by ACC Resin Statistic Report. This value was used to represent a more industry wide average value to account for facilities that did not participate in the LCI inventory. Actual reported figures were lower than the industry average.

References: A-51, A-58, and A-62.

Source: Franklin Associates, A Division of ERG

To assess the quality of the data collected for EDC/VCM, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for EDC/VCM include direct measurements, information provided by purchasing and utility records, calculated from equipment specifications, and engineering estimates. All data submitted for EDC/VCM ranges from 2003-2004 and represents U.S. production.

A.11. POLYVINYL CHLORIDE (PVC) RESIN PRODUCTION

PVC resin is produced by suspension, emulsion, mass, or solution polymerization of VCM. The data presented in this appendix represents suspension polymerization.

In the suspension process, VCM and initiators are mixed with water and kept in the form of aqueous droplets by agitation and suspension stabilizers. The polymerization generally is carried out in a nitrogen atmosphere in large agitated reactors. The reaction time is typically about 12 hours, and conversion of VCM approaches 90 percent. After polymerization, the unreacted monomer is removed and recycled. The polymer is blended with additives and modifiers and centrifuged to remove water. The resin is then dried and packaged for shipment.

Table A-11 presents the data for the production of PVC resin by suspension polymerization. Data for the production of PVC were provided by three leading producers (3 plants) in North America to Franklin Associates under contract to Plastics Division of the American Chemistry Council (ACC). Scrap is produced as a coproduct during this process. A mass basis was used to partition the credit for the scrap.

As of 2003 there were 12 PVC producers and 25 PVC plants in the U.S. (Reference A-52). While data was collected from a small sample of plants, the PVC producers who provided data for this module verified that the characteristics of their plants are representative of a majority of North American PVC suspension technology production. The average dataset was reviewed and accepted by all PVC data providers.

To assess the quality of the data collected for PVC, the collection methods, technology, industry representation, time period, and geography were considered. The data collection methods for PVC include direct measurements, information provided by purchasing and utility records, calculated from equipment specifications, and engineering estimates. All data submitted for PVC ranges from 2003-2004 and represents U.S. production.

Table A-11. Data for the Production of Polyvinyl Chloride (PVC) Resin

	English units (Basis: 1,000 lb)			Total Energy Thousand Btu	SI units (Basis: 1,000 kg)		Total Energy GigaJoules
Material Inputs							
Vinyl Chloride Monomer	1,001	lb			1,001	kg	
Water Consumption	121	gal			1,010	liter	
Energy Usage							
Process Energy							
Electricity (grid)	74.4	kwh		766	164	kwh	1.78
Electricity (cogeneration)	273	cu ft	(1)	306	17.1	cu meters	0.71
Natural gas	925	cu ft		1,036	57.7	cu meters	2.41
Total Process				2,108			4.91
Environmental Emissions							
Atmospheric Emissions							
Chlorine	0.010	lb	(2)		0.010	kg	
HCFC-22	0.0010	lb	(2)		0.0010	kg	
Hydrochloric Acid	1.0E-04	lb	(2)		1.0E-04	kg	
Other Organics	0.039	lb			0.039	kg	
Particulates (unknown)	0.087	lb			0.087	kg	
Vinyl Chloride	0.039	lb	(3)		0.039	kg	
Dioxins	1.1E-10	lb	(4)		1.1E-10	kg	
Solid Wastes							
Landfilled	1.09	lb			1.09	kg	
Burned	5.2E-04	lb			5.2E-04	kg	
Waterborne Wastes							
Ammonia	0.0010	lb	(2)		0.0010	kg	
BOD	0.012	lb			0.012	kg	
Chromium (unknown)	1.0E-04	lb	(2)		1.0E-04	kg	
COD	0.068	lb			0.068	kg	
Cyanide	1.0E-06	lb	(2)		1.0E-06	kg	
Nitrates	0.010	lb	(2)		0.010	kg	
Oil	0.0010	lb	(2)		0.0010	kg	
Phenol	9.9E-05	lb			9.9E-05	kg	
Suspended solids	0.16	lb			0.16	kg	
Zinc	1.0E-04	lb	(2)		1.0E-04	kg	
Dioxins	2.9E-10	lb	(4)		2.9E-10	kg	

Note: No additives or plasticizers were included in this data.

(1) The electricity amount from cogeneration is assumed to be produced from natural gas at a 50% efficiency.

(2) This emission was 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.

(3) This vinyl chloride emission was provided by the Vinyl Institute, based on 2011 Vinyl Chloride TRI reported values and 2011 PVC production reported by ACC Resin Statistic Report. This amount includes both the EDC/VCM plant as well as the PVC plant. This value was used to represent a more industry wide average value to account for facilities that did not participate in the LCI inventory. Actual reported figures were lower than the industry average.

(4) This emission was provided by the Vinyl Institute based on 2011 Dioxin TRI values and listed EDC capacity for the site assuming an operating rate at EDC capacity. Molar ratios were used to convert to units for PVC. These amounts were calculated as toxic equivalent values (TEQ).

References: A-60 and A-62

Source: Franklin Associates, A Division of ERG

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