



United States
Environmental Protection
Agency

EPA/600/R-16/176 | August 2017 | www.epa.gov/research

Life Cycle Inventory (LCI) Data-Treatment Chemicals, Construction Materials, Transportation, On-site Equipment, and Other Processes for Use in Spreadsheets for Environmental Footprint Analysis (SEFA): Revised Addition



Office of Research and Development
National Risk Management Research Laboratory
Land and Materials Management Division

***Life Cycle Inventory (LCI) Data-Treatment
Chemicals, Construction Materials,
Transportation, On-site Equipment, and Other
Processes for Use in Spreadsheets for
Environmental Footprint Analysis (SEFA):
Revised Addition***

Submitted Under
Approved QA ID #S-20578-QP-1-0

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Notice

The research has been subject to the Agency's review and has been approved for publication as a US EPA document. Use of the methods or data presented here does not constitute endorsement or recommendation for use. Mention of trade names or commercial products does not constitute endorsement or recommendation.

The appropriate citation for this report is:

Randall, P., Meyer, D., Ingwersen, W., Vineyard, D., Bergmann, M., Unger, S., and Gonzalez, M., 2016. *Life Cycle Inventory (LCI) Data- Treatment Chemicals, Construction Materials, Transportation, On-site Equipment, and Other Processes for Use in Spreadsheets for Environmental Footprint Analysis (SEFA): Revised Addition*. U.S. Environmental Protection Agency, Office of Research and Development, Cincinnati, OH. EPA/600/R-16/176a.

Abstract

This report estimates environmental emission factors (EmF) for key chemicals, construction and treatment materials, transportation/on-site equipment, and other processes used at remediation sites. The basis for chemical, construction, and treatment material EmFs is life cycle inventory data extracted from secondary data sources and compiled using the openLCA software package. The US EPA MOVES 2014 model was used to derive EmFs from combustion profiles for a number of transportation and on-site equipment processes. The EmFs were calculated for use in United States Environmental Protection Agency's Spreadsheets for Environmental Footprint Analysis. EmFs are reported for cumulative energy demand, global warming potential (GWP), criteria pollutants (e.g. NO_x, SO_x, and PM₁₀), hazardous air pollutants, and water use.

Foreword

Congress charges the U.S. Environmental Protection Agency (EPA) with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

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This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by U.S. EPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Cynthia Sonich-Mullin, Director
National Risk Management Research Laboratory

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List of Abbreviations and Acronyms

AFCEE	United States Air Force Center for Engineering and the Environment
ARB	California Air Resources Board
ASTM	American Society for Testing and Materials
BMP	Best Management Practice
BOD	Biological Oxygen Demand
BSFC	MOVES output for Fuel Consumption
BTS	United States Department of Transportation's Bureau of Transportation Statistics
Btu	British thermal unit
CAH	Chlorinated Aliphatic Hydrocarbons
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act of 1980
CED	Cumulative Energy Demand
CF	Characterization Factor
CFC	Chlorofluorocarbon
CH ₄	Methane
cm	Centimeter
CNG	Compressed Natural Gas
CO ₂	Carbon dioxide
CO ₂ e	Carbon dioxide equivalents of global warming potential
COC	Contaminant Of Concern
COD	Chemical Oxygen Demand
CSTR	Continuous Stirred Tank Reactor
CtG	Cradle to Gate
CVOC	Chlorinated Volatile Organic Compound
cy	cubic yards
DNAPL	Dense Non-Aqueous Phase Liquid
DOD	United States Department of Defense
DOE	United States Department of Energy
EERE	United States Department of Energy Office of Energy Efficiency and Renewable Energy
EIA	United States Energy Information Administration
EIPPCB	European Integrated Pollution Prevention and Control Bureau
ELCD	European Reference Life Cycle Database
EmF	Emission Factor
EPA	United States Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
ET	Evapotranspiration
ETSC	United States Environmental Protection Agency Engineering Technical

Support Center

FBR	Fluidized Bed Reactor
FHWA	Federal Highway Administration
FML	Flexible Membrane Liner
FS	Feasibility Study
ft	feet
FU	Functional Unit
GAC	Granular Activated Carbon
gal	gallon
GHG	Greenhouse Gas
GWP	Global Warming Potential
gpm	gallons per minute
GR	Green Remediation
HAP	Hazardous Air Pollutant as defined by the Clean Air Act
HDPE	High Density Polyethylene
hp	horsepower
HWI	Hazardous Waste Incinerator
IMAA	International Mastic Asphalt Association
IPCC	Intergovernmental Panel on Climate Change
ISCO	In-Situ Chemical Oxidation
ISO	International Organization for Standardization
ITRC	Interstate Technology & Regulatory Council
kg	kilogram
kW	kilowatt
kWh	kilowatt-hour
lbs.	pounds
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LHD	Light Heavy Duty engine
LPG	Liquefied Petroleum Gas
LSD	Low-Sulfur Diesel
MA	Mastic Asphalt
MCL	Maximum Contaminant Level
MHD	Medium Heavy Duty engine
MJ	Mega Joule
MMBtu	Million British thermal units
MOVES	Environmental Protection Agency's Motor Vehicle Emission Simulator
mpg	mile per gallon
mph	miles per hour
MT	Metric Ton(s)

MW	Megawatt
MWh	Megawatt-hour
NAICS	North American Industry Classification System
NETL	United States Department of Energy National Energy Technology Laboratory
N ₂ O	Nitrous Oxide
NO _x	Nitrogen Oxides (e.g., nitrogen dioxide)
NONROAD	A term used by regulators to classify engines in order to control their emissions
NPL	National Priorities List
NREL	United States Department of Energy National Renewable Energy Laboratory
NRMRL	United States Environmental Protection Agency National Risk Management Research Laboratory
O&M	Operations and Maintenance
OPC	Ordinary Portland Cement
ORD	United States Environmental Protection Agency Office of Research and Development
OSRTI	United States Environmental Protection Agency Office of Superfund Remediation and Technology Innovation
OSWER	United States Environmental Protection Agency Office of Solid Waste and Emergency Response
PM ₁₀	Particulate Matter (particles 10 µm or less in diameter)
PM _{2.5}	Particulate Matter less than 2.5 µm in diameter
POTW	Publicly Owned Treatment Works
psi	pounds per square inch
PV	Photovoltaic
PVC	Polyvinyl Chloride
RCRA	Resource Conservation and Recovery Act of 1976, as amended
RER	Code used byecoinvent for Europe
RI	Remedial Investigation
RMC	Ready Mixed Concrete
SCTG	Standard Classification of Transported Goods
SEFA	Spreadsheets for Environmental Footprint Analysis
SO _x	Sulfur Oxides (e.g., sulfur dioxide)
S-PVC	Polyvinyl Chloride, suspension process
SQL	Structured Query Language
STD	United States Environmental Protection Agency Sustainable Technology Division
THC	Total gaseous hydrocarbons
Tonne	Metric ton(s)
TRACI	Tool for the Reduction and Assessment of Chemicals and Other

Environmental Impacts

TRI	Environmental Protection Agency 's Toxic Release Inventory
ULSD	Ultra-Low Sulfur Diesel
USACE	United States Army Corps of Engineers
USLCI	United States Life Cycle Inventory
VCM	Vinyl Chloride Monomer
VOCs	Volatile Organic Compounds
WPPA	Wet-Process Phosphoric Acid
wt	weight
yr	year

Acknowledgements

An EPA project team coordinated its efforts to produce this report. Personnel from EPA’s Region IX (San Francisco, CA) and from the Life Cycle Research Center within the National Risk Management Research Laboratory (Cincinnati, OH) worked on this report. Our thanks and appreciation is extended to all these participants as well as the project team members:

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Donald Vineyard	ORISE Researcher, Cincinnati, OH

We appreciate the effort of peer reviewers who greatly improved the report: Briana Niblick (EPA, Cincinnati, OH) and Gurbakhash Bhandar (EPA, Research Triangle Park, NC).

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1.0 Study Overview and Objectives

1.1 Introduction

For remediation activities, chemicals, construction and treatment materials, nonroad vehicles, onsite diesel generators and other equipment are used to improve environmental and public health conditions. Cleanup activities use energy, water, and natural resources and create an environmental footprint based on their life cycles. To minimize the environmental footprints of remediation sites, the United States Environmental Protection Agency (EPA) encourages “green remediation” practices that consider all environmental effects of remedy implementation and incorporates strategies to minimize them. The term green remediation is documented in a 2008 report entitled “Green Remediation: Incorporating Sustainable Environmental Practices into Remediation of Contaminated Sites” (USEPA, 2008b). EPA defines “green remediation” as the practice of considering all the environmental effects of implementing a remedy, and incorporating options to minimize the environmental footprint of cleanup actions. This definition is a departure from the term “sustainable remediation” because green remediation focuses on the environmental aspect of a project, whereas sustainable remediation addresses environmental, social, and economic aspects of the cleanup actions (green remediation is sometimes used interchangeably with greener cleanups). Green remediation strategies may include a detailed analysis in which the remedy is closely examined and large contributions to the footprint are identified. Steps, therefore, may be taken to reduce the footprint while meeting regulatory requirements driving the cleanup (USEPA, 2012a).

In the last few years, EPA has implemented several case studies, which highlight the net environmental gains, as well as the challenges to minimize environmental footprints in cleanup actions (ITRC (Interstate Technology & Regulatory Council), 2011; USEPA, 2008a, 2010a, 2010b, 2011, 2013a, 2013b, 2013c, 2014a; USEPA Region 7, 2015). Besides EPA efforts, other Federal and state cleanup programs (McDonough, Woodward, Doherty, & Underhill, 2013) have begun to consider how remedial actions could lower their environmental footprint. In addition, there has been substantial industry effort and DOD effort to determine how green remediation should be defined and implemented. As of 2015, the following tools/spreadsheets are the most prominent for estimating the potential environmental burdens of remediation projects:

- Spreadsheets for Environmental Footprint Analysis (SEFA) – developed by EPA in 2012 (Version 1) updated in 2013 (Version 2) and most recently updated in August 2014 (Version 3).
- SiteWise – developed by Battelle, the Naval Facilities Engineering Command, and the U.S. Army Corps of Engineers (USACE) in 2010 (Version 1), 2012 (Version 2), and 2013 (Version 3).
- Sustainable Remediation Tool (SRT™) – developed by the U.S. Air Force Center for Engineering and the Environment (AFCEE) in 2009 (Version 1) and 2011 (Version 2) Currently unavailable as of January 29, 2016.
- SimaPro® and GaBi®, two commercial life cycle assessment (LCA) tools with extensive databases.

EPA developed the Spreadsheets for Environmental Footprint Analysis (SEFA) to estimate energy usage, greenhouse gas emissions, air pollutants, and hazardous air pollutants (HAPs). SEFA was originally developed for internal use by EPA staff and contractors. It was used in earlier formats within EPA, and was made publicly available in its current format in 2012 for the benefit of other users. It was last updated in August 2014. SEFA is based on life cycle thinking and designed to be compatible with EPA’s report: “Greener Cleanups Methodology for Understanding and Reducing a Project’s Environmental Footprint” (USEPA, 2012a). An overview of the general steps in performing an environmental footprint analyses is shown in Figure 1.

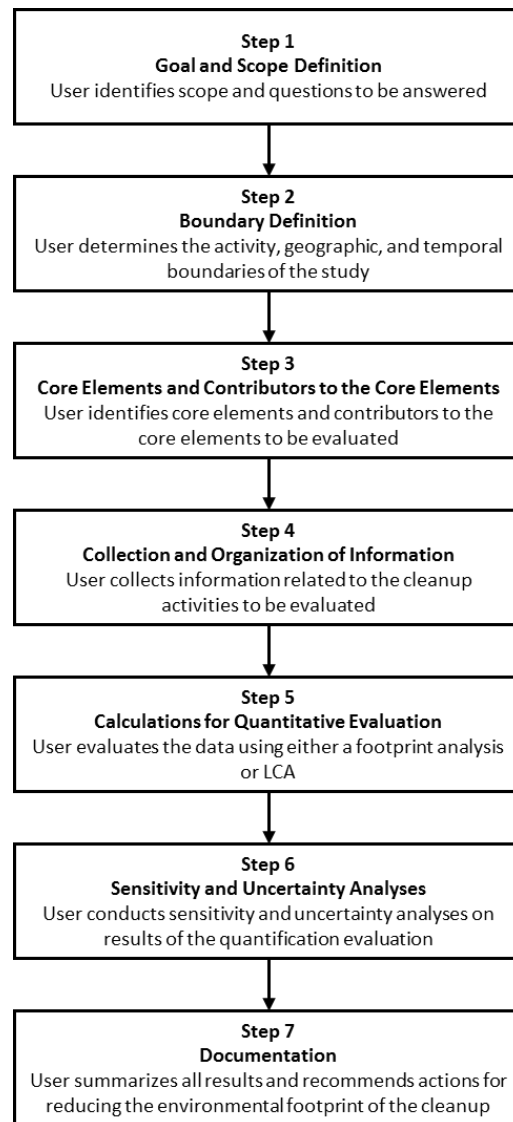


Figure 1. The steps of an environmental footprint analysis (ASTM 2013b).

Reducing a project’s environmental footprint is based on life cycle thinking. EPA’s 2006 document, “Life Cycle Assessment: Principles and Practice,” provides an overview of life cycle assessment (LCA) and describes the general uses and major components of LCA. Life cycle

assessment may be a cradle to grave, cradle to gate, or gate-to-gate approach for assessing industrial systems and/or activities. Cradle to grave begins with the gathering of raw materials from the earth to create the product and ends at the point when all materials are returned to the earth. LCA evaluates all stages of a product's life from the perspective they are interdependent, meaning that one operation leads to the next. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product life cycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, ultimate product disposal, etc.). By including impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection (USEPA, 2006).

At the core of the LCA process is the life cycle inventory (LCI). An LCI quantifies all energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity. The level of accuracy and detail of data collected will determine the accuracy and reliability of the subsequent impact assessment results. The inventory can be separated by life cycle stage, media (air, water, and land), specific processes, materials, or any combination thereof.

EPA's "Life Cycle Assessment: Inventory Guidelines and Principles" and the "Guidelines for Assessing the Quality of Life Cycle Inventory Analysis" provide a framework for performing an inventory analysis and assessing the quality of data used for an LCA (USEPA, 1993c, 1995b). In addition, ASTM's E2893 standard "Standard Guide for Greener Cleanups" provides more details on steps required for a quantitative evaluation in identifying opportunities to reduce the environmental footprint of a selected remedy. Shown in Figure 1, steps may include: 1. Goal and Scope Definition; 2. Boundary Definition; 3. Core Elements and Contributors to the Core Elements; 4. Collection and Organization of Information; 5. Calculations for Quantitative Evaluation; 6. Sensitivity and Uncertainty Analyses; and 7. Documentation (ASTM, 2013b).

1.2 Study Objectives

The study objectives are as follows:

- Collect secondary data to model LCI for remediation chemicals, materials, and processes specified by US EPA's Region 9 Office.
- Develop life cycle inventories for the specified chemicals and materials using OpenLCA and the collected secondary data.
- Perform motor vehicle emissions simulations to model operation of vehicles and equipment associated with remediation sites.
- Develop life cycle inventories for the vehicles and equipment using OpenLCA and the emissions simulation data.
- Create and apply a footprint methodology in OpenLCA to quantify environmental emission factors (EmFs) for use in SEFA.

- Document the methodology and calculations used to derive the reported material, chemical, and process EmFs.
- Document the methodology used to model use of vehicles and equipment.
- Create EmFs for analytical testing activities promulgated under the Clean Water Act (CWA) section 304(h).

1.3 Intended Audience

The primary intent of the report is to document and communicate the methodology used to derive the chemical, material, and process EmFs and support their use by EPA's Region 9 as input to SEFA. Once the EmFs are input into the SEFA method, it will assist Federal, state, and local government officials, industry, EPA site contractors, and NGOs with evaluating and implementing activities to reduce the potential footprint of environmental cleanups. EPA Region 9 Superfund and RCRA staff requested the information through EPA's Engineering Technical Support Center (ETSC). The Sustainable Technology Division (STD) within the National Risk Management Research Laboratory (NRMRL) performed this undertaking. The underlying inventory models described in this report may be useful to LCA practitioners and anyone else working in the area of chemical and material sustainability. Chemical, material, and process LCIs developed from publically available secondary data are included in the report for transparency. Proprietary LCIs obtained from ecoinvent have been excluded in accordance with copyright laws and only the applicable ecoinvent process name is reported.

2.0 Material LCI Modeling and Emission Factor Results

2.1 Methodology

Although there are specific calculation procedures for performing LCI analysis by hand, these procedures can be made more efficient and automated by using computer software. In this study, the preferred method was to use open-source computer software coupled with a commercially available inventory database to promote consistency between material models. The LCA software selected for this study is OpenLCA version 1.4, as created and maintained by GreenDelta. The database selected for this study is the proprietary ecoinvent version 2.2 database developed by the Swiss Center for Life Cycle Inventories. The database goes back to 1990s and contains over two thousand unit process inventories. Although the unit process LCIs in ecoinvent are proprietary, it is permissible to release system-level EmFs calculated for this project using ecoinvent data because the aggregated nature of the footprint categories at the system (i.e., cradle-to-gate) level sufficiently mask copyrighted data. For some materials included in this study, either no unit process LCI existed in ecoinvent or more relevant and preferable data from other secondary sources were identified. Additional secondary data sources can include government data (e.g., EPA's Toxics Release Inventory (TRI)), industry reports, engineering estimates based on estimated parameters, Kirk-Othmer Encyclopedia of Chemical Technology, Ullmann's Encyclopedia of Industrial Chemistry, journal articles, and other computer databases (e.g., US LCI). When applicable, new LCIs were created for the materials in OpenLCA using the best available secondary data.

This study examines cradle to gate (CtG) LCIs for the production of chemical and materials specified by EPA Region 9. LCIs developed in this study were constructed in accordance with ISO 14040 International standard documents on life cycle thinking (ISO, 1998, 2000, 2006a, 2006b) as well as the ASTM standard documents on greener and sustainable cleanups (ASTM, 2013a, 2013b). System boundaries for a CtG LCI include everything from the cradle (excavation of the raw materials and resources from the ground) to the end of the production process, or facility gate (Figure 2). For each material of interest, OpenLCA was used to model the material life cycle and construct the corresponding CtG LCI. Such a dataset can involve numerous individual unit processes throughout the supply chain (e.g., the extraction of raw resources, various primary and secondary production processes, transportation, etc.) and account for all resource inputs and process outputs associated with a chemical or material. Resource inputs include raw materials and energy use, whereas process outputs include manufactured products and environmental emissions to land, air, and water. The cradle to gate LCI models stop at the gate of the production process and therefore, do not include downstream and/or onsite cleanup activities such as onsite construction, implementation, monitoring, and decommissioning. All flows to and from the environment are defined as elementary flows in LCA and flows between unit processes are termed technosphere flows. The inputs and outputs are expressed in terms of a reference flow, or functional unit, for the chemical or material of interest. The chemicals and materials selected by Region 9 for inclusion in this study are listed in Table 1.

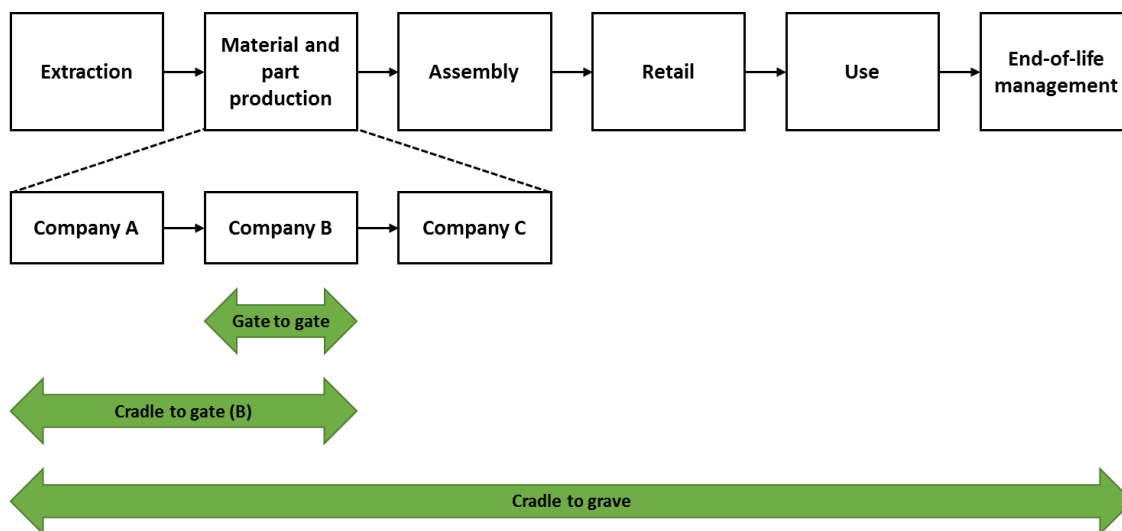


Figure 2. Cradle to grave, cradle to gate and gate to gate data sets as parts of the complete life cycle (EC 2011)

Table 1. Selected Chemicals and Materials for Emission Factor Development

Aluminum, Rolled Sheet	Lime, Hydrated, Packed	Primary Activated Carbon
Corn Ethanol, 95%	Mastic Asphalt	Ready Mixed Concrete
Corn Ethanol, 99.7%	Paving Asphalt	Regenerated Activated Carbon
Gravel/Sand Mix, 65% gravel	Petroleum Ethanol, 99.7%	Round Gravel
Hazardous Waste Incineration	Phosphoric Acid, 70% in water	Sand
High Density Polyethylene	Polyvinyl Chloride	Sodium Hydroxide, 50% in water
Hydrogen Peroxide, 50% in water	Portland Cement	
Iron (II) Sulfate, Hydrated	Potassium Permanganate	

Inventory analysis for this study involved sorting and aggregation of relevant elementary flows into the environmental footprint categories considered in SEFA. These categories include Cumulative Energy Demand (CED, MMBtu); Global Warming Potential on a 100-year time frame (GWP, lb. CO₂ equivalents); EPA criteria pollutants: nitrogen oxides (NO_x, lb.), sulfur dioxides (SO_x, lb.), particulate matter $\leq 10 \mu\text{m}$ (PM₁₀, lb.); hazardous air pollutants as defined by the EPA (HAPs, lb.) (USEPA, 2014b); and water use (gals). While the importance and relevance of NO_x, SO_x, PM₁₀, and HAPs are clear, explanations of CED, GWP, and Water Use are presented here for the benefit of the reader. The current list of HAPs, as defined by EPA, is provided in Appendix 1.

CED of an activity represents the direct and indirect energy use in units of MJ throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials. The total CED is composed of the fossil cumulative energy demand (i.e., from hard coal, lignite, peat, natural gas, and crude oil) and the CED of nuclear, biomass, water, wind, and solar energy in the life cycle. Typical upper heating values for primary energy resources required in the CED calculations were used in the ecoinvent datasets (Huijbregts et al., 2010).

GWP is based on the commonly accepted carbon dioxide (CO₂) equivalency factors published in the IPCC (2007) report. GWP is calculated to express the global warming impacts of a given gas relative to a similar mass of CO₂. Similarly, total GWP is calculated for a process by taking the masses of the gaseous emissions of the process multiplied by their respective GWPs and summed to arrive at the total GWP. The GWPs of various greenhouse gases are compared to determine which will cause the greatest integrated radiative forcing (i.e. energy absorbed) over the time horizon of interest (i.e., 100 years). Carbon dioxide, by definition, has a GWP of 1, regardless of the time used, because it is the gas being used as the reference. Besides CO₂, other GWP gases include methane (CH₄) and nitrous oxide (N₂O). The complete list of species of gases and their GWPs values for time horizons of 20, 100, and 500 years are in table 2.14 of the IPCC 2007 report (Solomon, 2007).

Given the concerns regarding depletion of water resources, the importance of tracking Water Use has grown significantly in recent years. For SEFA, this is performed by calculating the net freshwater use (water withdrawal – water discharge) for a system to determine the potential impact on water scarcity. Therefore, Water Use calculations in OpenLCA account for all elementary

freshwater input and output flows to a chemical or material LCI from river, lake, and well water sources. In some cases, unspecified water sources were included in secondary data sources and were tracked.

The sorting and aggregation of the inventory into the appropriate footprint categories was performed in openLCA. Sorting and categorical aggregation for footprinting is analogous to impact assessment in LCA. However, footprinting differs from impact assessment because the characterization factors (CF) used to translate the elementary flow values to appropriate category values typically have a value of 1 and result in EmFs as opposed to impact scores. This leads to a simple summation of all like elementary flows (F) from the CtG LCI into an EmF for each desired footprint category:

$$EmF = \sum_{i=1}^m \sum_{j=1}^n F_{i,j} \times CF_j$$

where, i , denotes the unit process, m is the maximum number of unit process represented in the LCI, j is an individual flow that contributes to a footprint indicator, and n is the maximum number of flows included in the footprint indicator. For example, the HAPs value for the production of ethanol would be the summation of the masses of all HAP substances emitted from growing the corn, transporting and processing it into ethanol, and distilling the ethanol to high purity. The exceptions to this approach are the categories of CED and GWP where inventory flows are converted to energy (MMBtu) and carbon dioxide equivalents (CO₂e), respectively. In these cases, the characterization factors have values other than 1 as defined in each methodology's documentation. Although CED is still a footprinting category because it makes no evaluation of the impact of energy demand, GWP does consider the potency of substances for inducing global warming when converting to CO₂e and is therefore more like an impact indicator.

The material emission factors developed for each of the footprint categories are intended for implementation in EPA's SEFA workbooks. For example, in-situ oxidants such as potassium permanganate or hydrogen peroxide may be used in a cleanup. The emission factors for the oxidants will be stored as default values in SEFA. An end-user remediating a site involving insitu oxidation can specify how much potassium permanganate or hydrogen peroxide is used as part of the site's remediation activities and the SEFA method will incorporate the material's production footprint (e.g., CED (MMBtu/lbs. of material produced) or GWP (lbs. of CO₂e per lb. of material produced) into the life cycle environmental footprint for the remediation site.

As with any model, there is some uncertainty in the calculated EmFs. LCI quality issues have been broadly discussed since the 1990's (USEPA, 1995b). More recently, ecoinvent has discussed the basic structure of the database and data quality (B. P. Weidema et al., 2013). Data quality is affected by certain variables such as the dependence on data from different countries, different unit operations, and different sources. At the LCI level, data uncertainty may be introduced due to data inaccuracy, data gaps, lack of representative inventory data, model uncertainty (i.e., static vs. dynamic, linear vs. non-linear modeling), or spatial and temporal variability (USEPA, 2012b).

Quantification of uncertainty of the reported EmFs was not performed as part of this work because a lack of ample data describing potential value distributions for the various data contained within the material LCIs.

Qualitatively, use of the reported EmFs for decision-making should only be done with acknowledgement of the assumptions employed for this study, which may affect the accuracy and certainty of the factors. This study assumed that LCI datasets developed with ecoinvent data for chemical processes in Europe are transferable to the US. In general, the chemistry, mass balances, and energy balances are similar but there may be slight differences. For example, electricity grid mixes for Europe are different from US, which may be significant to the calculated EmFs if electricity production is a dominant part of the material life cycle. Similarly, transportation modeling can differ between Europe and US, in terms of both distance and mode of transport. Finally, waste management has not been included in the material LCIs because there are large data gaps for this part of the life cycle in LCI modeling in general, especially for waste processing in the US.

It is important to note the EmFs reported for this study should not be confused with characterization factors for life cycle impact assessment. Except for GWP, they do not attempt to determine the fate and transport of total emissions nor do they attempt to determine the risk to humans or the environment arising from these emissions. Similarly, they infer no judgments regarding the impacts of obtaining and using natural resources.

2.2 Corn Ethanol, (95% in H₂O or 99.7% Dehydrated)

2.2.1 Introduction

In general, ethanol or ethyl alcohol (CH₃CH₂OH) is an organic chemical with many applications (e.g., transportation, alcoholic beverages; solvent; raw material in chemical synthesis; fuel; environmental remediation). For environmental cleanups, ethanol is used for enhanced in-situ anaerobic bioremediation of groundwater. Enhanced in situ anaerobic bioremediation has emerged in recent years as a remediation strategy for chlorinated aliphatic hydrocarbons (CAHs) in groundwater. Advantages include complete mineralization of the contaminants in-situ with little impact on infrastructure and relatively low cost compared to more active engineered remedial systems (e.g., groundwater extraction, permeable reactive iron barriers, or chemical oxidation). Regulatory acceptance of enhanced anaerobic bioremediation has evolved over the last several years under various federal programs, including the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and the Resource Conservation and Recovery Act (RCRA) (Leeson, Beevar, Henry, Fortenberry, & Coyle, 2004)

Ethanol can be produced as a biofuel from sugars in sugar cane or sugar beet, or from starch hydrolyzed into sugars derived from crops such as maize, wheat, or cassava (Worldwatch Institute, 2007). Most ethanol production in the US uses grains (i.e., corn or “maize”) as the feedstock. Production of corn-based ethanol has grown from less than 2 billion gallons in 1999 to over 14 billion gallons in 2014 (RFA, 2015).

Ecoinvent data indicate that 1 kg of 95% corn ethanol has a number of processes that are associated with varying quantities of kg CO_{2e} emitted. However, the production of corn outweighs these values, where corn production sequesters a greater value of kg CO_{2e} than the summed processes associated with varying quantities of kg CO_{2e} emitted.

2.2.2 LCI Modeling

- Functional unit: 1 kg of ethanol (either 95% or 99.7% after molecular sieve dehydration).
- System boundaries: the main processes for corn ethanol are the cultivation and production of corn and subsequent fermentation and distillation of ethanol as shown in Figure 3. An additional molecular sieve process is required after distillation if a 99.7 % dehydrated ethanol product is desired.

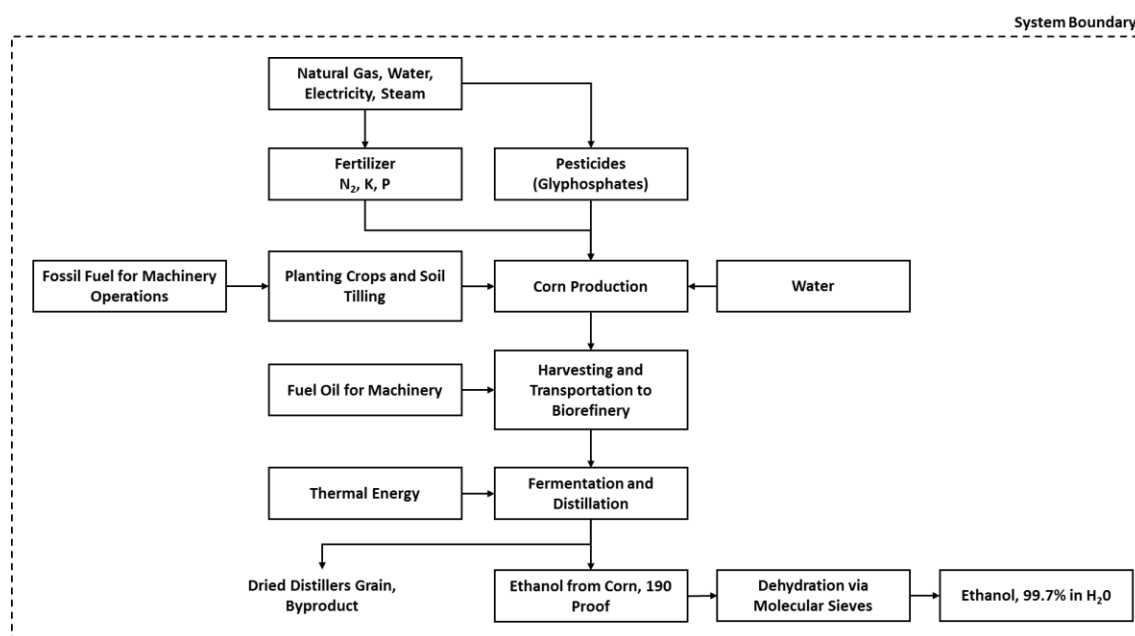


Figure 3. Production of 99.7% corn ethanol as presented by (Jungbluth et al., 2007)

- Inventory data: “ethanol, 95% in H₂O, from corn, at distillery – US”; “ethanol, 99.7%, in H₂O, from biomass, at distillery – US”; ecoinvent v2.2; (Jungbluth et al., 2007).

2.2.3 Emission Factors

- Unit conversion calculations were necessary to convert from SI units (OpenLCA results) to English units (SEFA factors). These calculations are shown here for 95% Corn Ethanol, but are the same for all chemicals and materials covered in this report. The only exception is ready mixed concrete because it is reported on a volume basis instead of mass.

Cumulative Energy Demand (CED)

$$\frac{(7.39 \times 10^{-4} \text{ MJ}) \times (9.48 \times 10^{-4} \text{ MMBtu}) \times (1 \text{ kg})}{\text{MMBtu}} = 3.18 \times 10^{-2} \frac{\text{kg}}{\text{lb}}$$

Global Warming Potential (GWP 100)

$$(-1.99 \times 10^{-2} \text{ kg } \frac{\text{CO}_2 \text{ eq}}{\text{kg}}) \times (2.2 \text{ lb}) \times (\frac{1 \text{ kg}}{2.2 \text{ lb}}) = -1.99 \times 10^{-2} \text{ lb}$$

Hazardous Air Pollutants (HAPs)

$$(8.46 \times 10^{-5} \text{ kg } \frac{\text{HAPs}}{\text{kg}}) \times (2.2 \text{ lb}) \times (\frac{1 \text{ kg}}{2.2 \text{ lb}}) = 8.46 \times 10^{-5} \text{ lb}$$

Nitrogen Oxides (NO_x)

$$(4.25 \times 10^{-3} \text{ kg NO}_x \frac{\text{lb NO}_x}{\text{kg}}) \times (\frac{1 \text{ kg}}{2.2 \text{ lb}}) \times (2.2 \text{ lb}) = 4.25 \times 10^{-3} \text{ lb}$$

Sulfur Oxides (SO_x)

$$(3.03 \times 10^{-3} \text{ kg } \frac{\text{SO}_x}{\text{kg}}) \times (2.2 \text{ lb}) \times (\frac{1 \text{ kg}}{2.2 \text{ lb}}) = 3.03 \times 10^{-3} \text{ lb SO}_x$$

Particulate Matter (PM₁₀)

$$(4.69 \times 10^{-4} \text{ kg PM}_{10}) \times (2.2 \text{ lb}) \times (\frac{1 \text{ kg}}{2.2 \text{ lb}}) = 4.69 \times 10^{-4} \text{ lb PM}_{10}$$

Water Use

$$m^3 H$$

$$\frac{(3.60 \times 10^{-2} \text{ kg}_2O) \times (10001 \text{ m}^3 L) \times (0.2642 \text{ gal/L}) \times (21.2 \text{ kg lb})}{\text{lb H}_2O} = 4.32 \text{ gal}$$

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM10 (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
Corn Ethanol, 95%	3.18E-02	-1.99E-02	8.46E-05	4.25E-03	4.69E-04	3.03E-03	4.32E+00
Corn Ethanol, 99.7%	3.24E-02	5.91E-02	8.70E-05	4.31E-03	4.72E-04	3.10E-03	4.35E+00

Table 2. SEFA Emission Factors for Corn Ethanol

□ Emission Factor Calculation Results

2.3 Petroleum Ethanol, 99.7%

2.3.1 Introduction

As an alternative, ethanol is produced by extracting crude oil and making ethylene. Ethylene can be produced from either crude oil or natural gas recovered from conventional wells or shale rock, but we have based this scenario on crude oil from conventional wells only. With ethylene from crude, the life cycle begins with the extraction of petroleum crude oil from conventional wells and pumping it into storage tanks. From storage tanks, crude oil is transported (i.e., ocean freighter, pipelines) to an oil refinery where it is refined into naphtha. In the production of naphtha from crude oil, the proportion of the individual fractions can vary greatly and can produce LPG, paraffinic naphtha, heavy naphtha, kerosene, diesel, and residual oil, depending on the crude oil composition. Naphthas, which are the most important feedstock for ethylene production, are mixtures of hydrocarbons in the boiling range of 30–200 °C. Processing of light naphthas (boiling range 30–90 °C), full range naphthas (30–200 °C) and special cuts (C₆–C₈ raffinates) as feedstock is typical for naphtha crackers (Hischier, 2007).

The production of ethanol from ethylene is due to the catalytic hydration of ethylene to ethanol. In direct catalytic hydration, ethanol is produced by the vapor-phase reaction of ethylene and water over a catalyst impregnated with phosphoric acid. For more details on the direct catalytic hydration process, see (Sutter, 2007).

2.3.2 LCI Modeling

- Functional unit: 1 kg of petroleum-based ethanol, 99.7% (anhydrous).
- System boundaries: the main processes for petroleum ethanol are the refinement and processing of crude to produce ethylene (Figure 4), which is then hydrated to make ethanol (Figure 5).

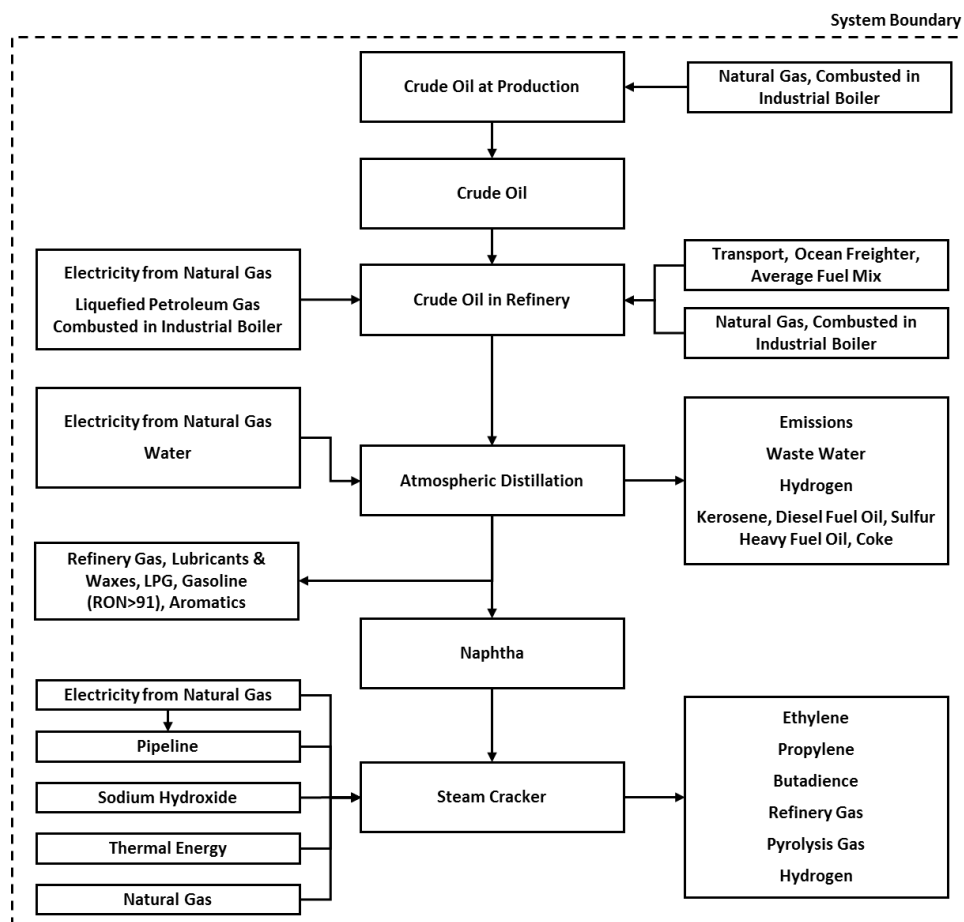


Figure 4. Production of ethylene as reported by (Ghanta, Fahey, & Subramaniam, 2014)

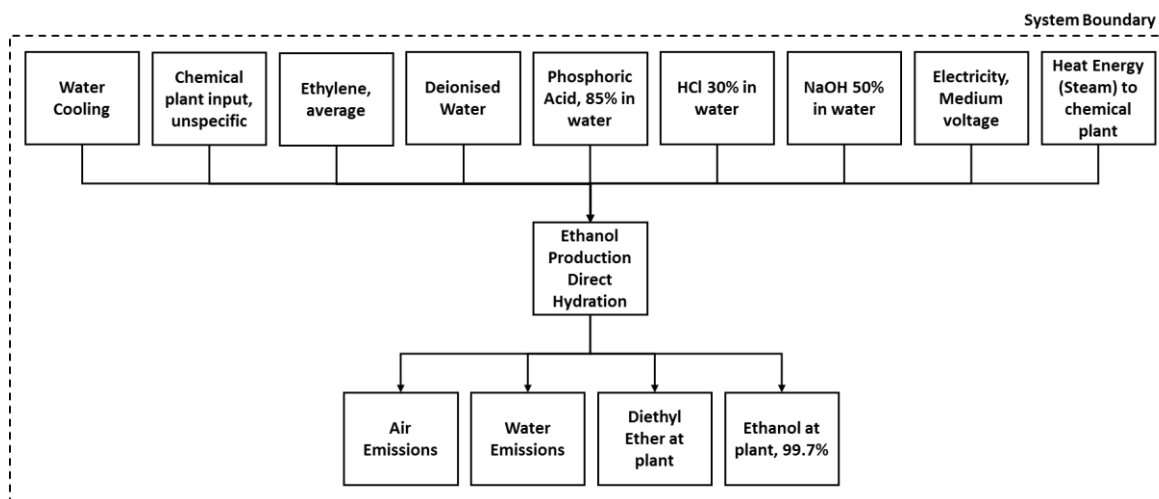


Figure 5. Production of anhydrous petroleum ethanol as reported by (Sutter, 2007)

- Inventory data: “ethanol from ethylene, at plant – RER”; ecoinvent v2.2; (Sutter, 2007).

2.3.3 Emission Factors

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM ₁₀ (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
Petroleum Ethanol, 99.7%	2.05E-02	1.25E+00	5.89E-05	1.99E-03	2.77E-04	2.14E-03	4.16E+00

- Emission Factor Calculation Results.

Table 3. SEFA Emission Factors for Petroleum Ethanol

2.4 Potassium Permanganate (KMnO₄)

2.4.1 Introduction

Potassium permanganate (KMnO₄) is industrially very important and an indispensable oxidant. It is used principally as an oxidizing agent in the following applications: municipal water treatment, wastewater treatment, chemical manufacturing and processing, aquaculture (fish farming), metal processing, and air and gas purification. In addition, potassium permanganate is used as a decoloring and bleaching agent in the textile and tanning industries, as an oxidizer in the decontamination of radioactive wastes, as an aid in the flotation processes used in mining, and in cleaning printed circuit boards (Pisarczyk, 2005; Reidies, 2000; USEPA, 2015c; USITC, 2010). For environmental applications, a concentrated KMnO₄ solution (typically 1-5 % is its optimal solubility) is generated on-site using dry potassium permanganate.

World production capacity for potassium permanganate is estimated to be 43000–51000 tons/yr., although actual demand is less than 30000 tons/yr. (Reidies, 2000). Carus Corporation was the only commercial producer of KMnO₄ in the US in 2009. KMnO₄ may be manufactured by a onestep electrolytic conversion of ferromanganese to permanganate, or by a two-step process involving the thermal oxidation of manganese (IV) dioxide to potassium manganate (VI), followed by electrolytic oxidation to permanganate. Carus markets permanganates under various trade names (AQUOX[®], CAIROX[®], LIQUOX[®], ECONOX[®], CARUSOL[®] and RemOx[®]) (Carus Corporation, 2009). Three grades of KMnO₄ are produced (i.e., free-flowing, technical, pharmaceutical). The free-flowing grade is produced by adding an anti-caking agent to the technical grade, preventing the particles from sticking together when in contact with moisture. The pharmaceutical grade must be at least 99% KMnO₄ by weight and involves additional recrystallization to remove impurities or to meet customer specifications. The three grades of KMnO₄ are generally interchangeable in their various applications, except for pharmaceutical applications.

2.4.2 LCI Modeling

- Functional unit: 1 kg of KMnO₄.

- System boundaries: the main processes for KMnO_4 are the mining and beneficiation of manganese ore, oxidation to manganese dioxide, and further oxidation to the final product (Figure 6).

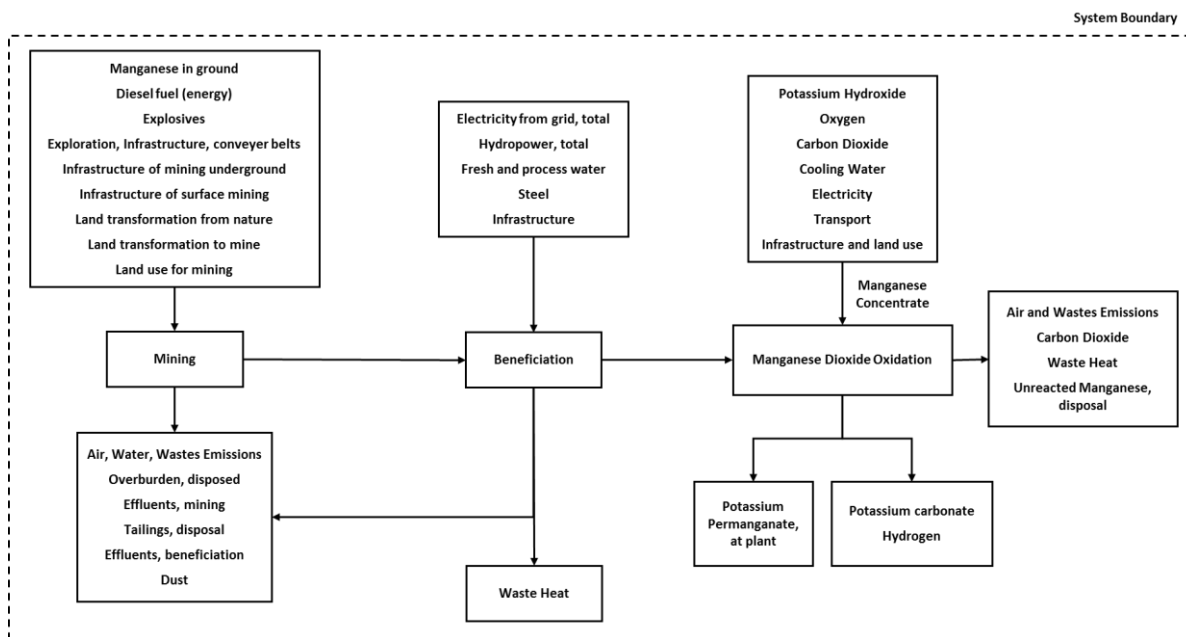


Figure 6. Production of KMnO_4 as reported by (Classen et al., 2007)

- Inventory data: “potassium permanganate, at plant – RER”; ecoinvent v2.2; (Sutter, 2007).

2.4.3 Emission Factors

- Emission Factor Calculation Results.

Table 4. SEFA Emission Factors for KMnO_4

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM10 (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
Potassium Permanganate	9.81E-03	1.16E+00	1.22E-04	2.34E-03	4.22E-04	3.20E-03	7.45E+00

2.5 Lime, Hydrated and Packed

2.5.1 Introduction

Hydrated lime refers to a dry calcium hydroxide powder produced from the calcination of limestone, a naturally occurring mineral that consists principally of calcium carbonate but may contain magnesium carbonate as a secondary component. Hydrated lime is widely used in aqueous systems as a low-cost alkaline chemical.

2.5.2 LCI Modeling

- Functional unit: 1 kg of hydrated lime, packed.
- System boundaries: the main processes involved with the production of hydrated lime are limestone mining, crushing, washing, calcination, and milling as shown in Figure 7.

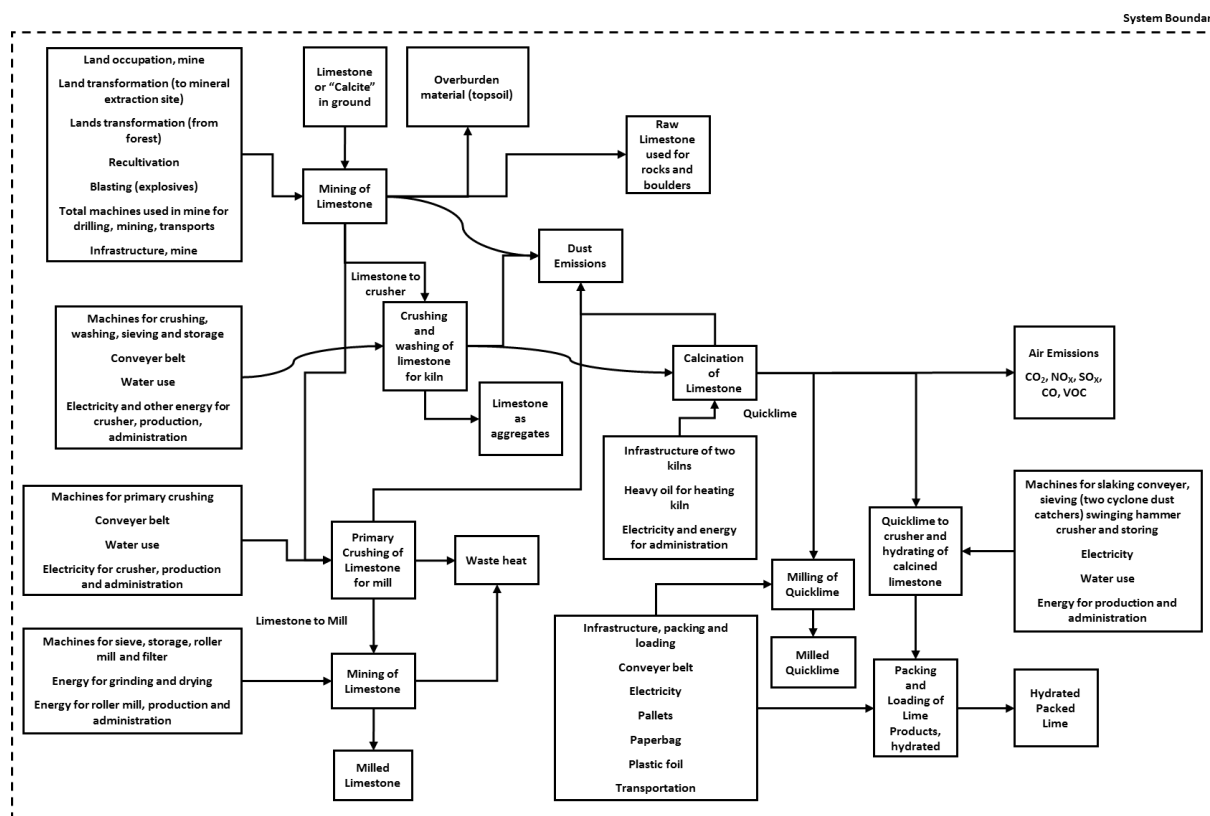


Figure 7. Production of hydrated lime as presented in (Kellenberger et al., 2007)

- Inventory data: “lime, hydrated, packed, at plant – CH”; ecoinvent v2.2; (Kellenberger et al., 2007).

2.5.3 Emission Factors

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM10 (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
Lime, Hydrated, Packed	2.06E-03	7.62E-01	6.57E-06	5.13E-04	1.30E-04	3.58E-04	2.94E-01

- Emission Factor Calculation Results.

Table 5. SEFA Emission Factors for Hydrated Lime

2.6 Sodium Hydroxide (NaOH), 50% in Water

2.6.1 Introduction

Sodium hydroxide, often referred to as caustic soda, or just caustic, is a strong base. It is typically produced as a coproduct with chlorine through the electrolytic decomposition of sodium chloride solutions (brines). According to the Chlorine Institute, in 2010, the U.S. chlor-alkali industry produced 11.6 million short tons of chlorine and 12.2 million short tons of caustic soda (American Chemistry Council, 2015).

Three basic processes (diaphragm, mercury, and membrane) account for almost all world chlorine capacity. Up to the end of the 20th century, the mercury cell technique dominated in Europe, while the diaphragm cell technique dominated in US and the membrane cell technique in Japan. Recently, new plants worldwide are based on the membrane cell technique. Generally, most producers operate their plants to make chlorine because it is hard to store and is used for derivatives like ethylene dichloride, phosgene, and epichlorohydrin. Caustic soda is generally sold on the merchant market and consumed in a myriad of uses (Linak & Inui, 2002). Due to customers' requirements, sodium hydroxide is produced commercially in two forms: as a 50 wt.% solution (most common) and less frequently in the solid state as prills, flakes, or cast shapes.

2.6.2 LCI Modeling

- Functional unit: 1 kg of sodium hydroxide, 50% in H₂O.
- System boundaries: the data set assumes a production mix of sodium hydroxide with 23.5% produced by diaphragm cell, 55.1% produced by mercury cell, and 21.4% produced by membrane cell. As shown in Figure 8, the same basic flow of primary materials applies to all three pathways.

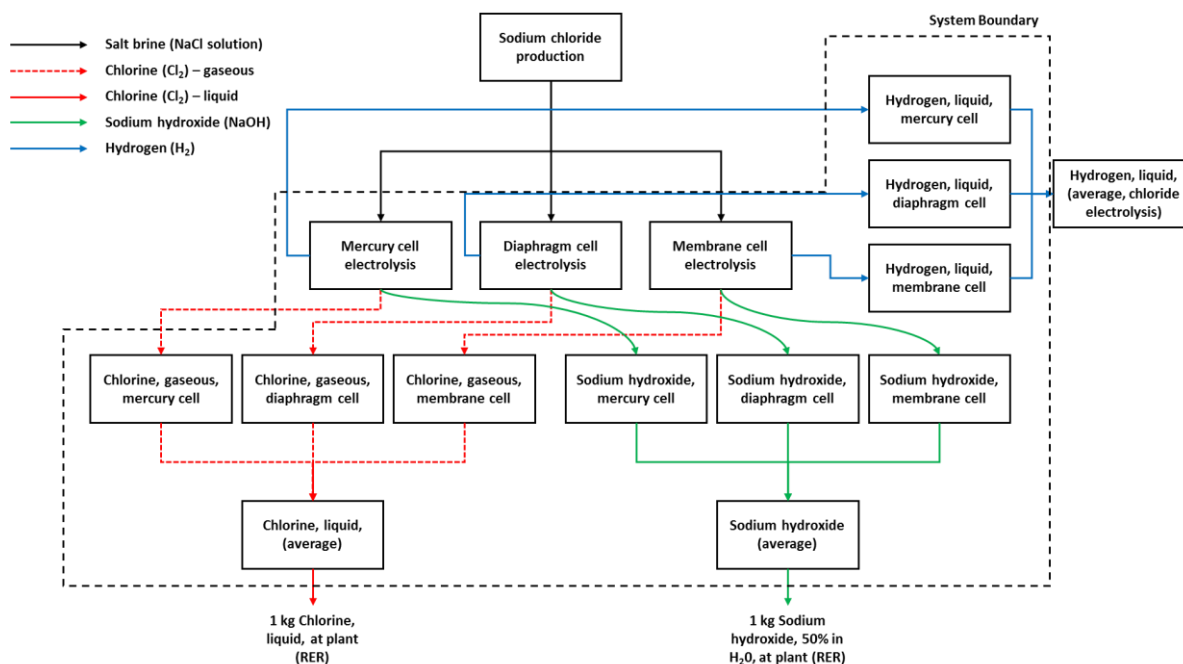


Figure 8. Production of average mix sodium hydroxide as shown in (Althaus et al., 2007)

- Inventory data: “sodium hydroxide, 50% in H₂O, production mix, at plant – RER”; ecoinvent v2.2; (Althaus et al., 2007).

2.6.3 Emission Factors

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NOx (lb/lb)	PM10 (lb/lb)	SOx (lb/lb)	Water Use (gals/lb)
Sodium Hydroxide, 50% in water	9.77E-03	1.09E+00	1.29E-04	1.94E-03	4.03E-04	3.52E-03	1.39E+01

- Emission Factor Calculation Results.

Table 6. SEFA Emission Factors for Sodium Hydroxide

2.7 Hydrogen peroxide, 50% in Water

2.7.1 Introduction

Hydrogen peroxide is ubiquitous in the environment. In surface water, photochemical processes generally produce H₂O₂. In the atmosphere H₂O₂ is generated by photolysis of O₃ (Wayne, 1988) or aldehydes (Calvert & Stockwell, 1983). H₂O₂ is a weakly acidic, nearly colorless, clear liquid that is miscible with water in all proportions. In addition, H₂O₂ is a strong oxidizing agent commercially available in aqueous solution over a wide range of concentrations. Aqueous H₂O₂ is sold in concentrations ranging from 3 to 86 wt. %, most often containing 35, 50, and 70 wt. %.

H₂O₂ is used in various industrial and environmental applications. Due to its characteristics as a strong oxidizing agent, H₂O₂ is widely used as a bleaching agent in the paper and the textile industry. Further important uses are disinfection applications, hydrometallurgical processes, or wastewater treatment. In dilute solutions, H₂O₂ acts as a very efficient antiseptic. With regard to SEFA, H₂O₂ is used as an in-situ chemical oxidant for remediation. *In situ* chemical oxidation (ISCO), a form of advanced oxidation process is an environmental remediation technique used for soil and/or groundwater remediation to reduce concentrations of targeted environmental contaminants to acceptable levels. ISCO is accomplished by injecting or otherwise introducing strong chemical oxidizers directly into the contaminated medium (soil or groundwater) to destroy chemical contaminants in place. It can be used to remediate a variety of organic compounds, including some that are resistant to natural degradation.

2.7.2 LCI Modeling

- Functional unit: 1 kg of hydrogen peroxide, in H₂O at plant.
- System boundaries: the production of 50% hydrogen peroxide involves bubbling oxygen through anthracene as shown in Figure 9.

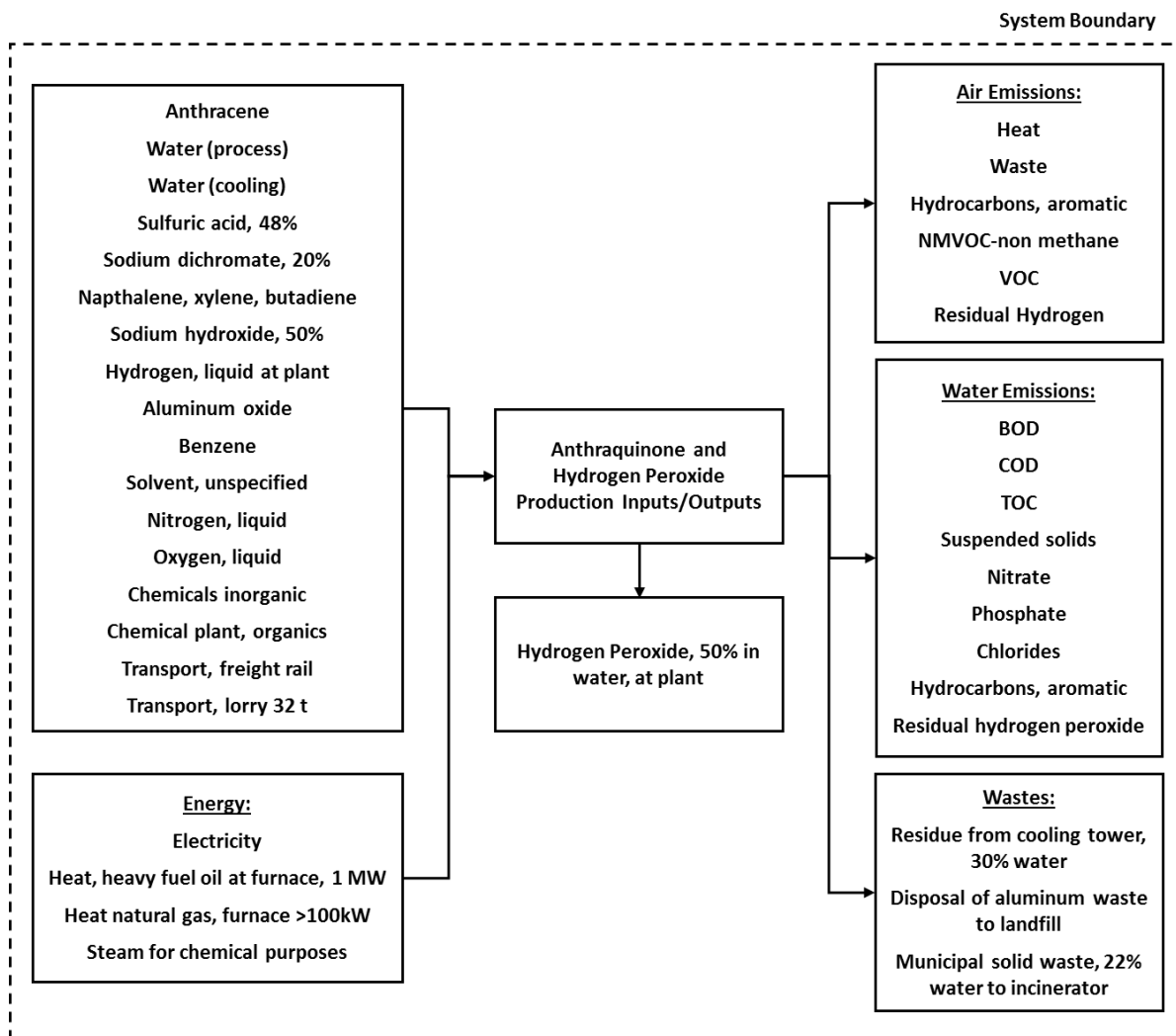


Figure 9. Production of hydrogen peroxide as shown in (Althaus et al., 2007).

- Inventory data: “hydrogen peroxide, 50% in H₂O, at plant – RER”; ecoinvent 2.2; (Althaus et al., 2007).

2.7.3 Emission Factors

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM10 (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
Hydrogen Peroxide, 50% in water	9.79E-03	1.19E+00	6.29E-05	1.42E-03	3.08E-04	2.40E-03	2.35E+01

- Emission Factor Calculation Results.

Table 7. SEFA Emission Factors for Hydrogen Peroxide

2.8 Phosphoric Acid, 70% in Water

2.8.1 Introduction

Pure, anhydrous phosphoric acid, H_3PO_4 , is a colorless, crystalline compound that is readily soluble in water. After sulfuric acid, phosphoric acid is the most important mineral acid in terms of volume and value. This is mainly due to the enormous demand for wet phosphoric acid for further processing to fertilizers (Schrödter et al., 2000).

Phosphoric acid is produced by either a wet process or thermal process. The majority of phosphoric acid, approximately 96 %, is produced using the wet-process phosphoric acid (WPPA) method (USEPA, 1993a). The thermal process uses a high amount of energy and produces strong phosphoric acid liquid (of about 85 wt. % of H_3PO_4), which is required for high-grade chemical production. Most of the WPPA produced worldwide is made with the dihydrate process (Althaus et al., 2007; Gard, 2005; Schrödter et al., 2000; USEPA, 1993b).

Phosphoric acid plays a critical role in the restoration of environmental sites contaminated with heavy metals. Phosphoric acid forms insoluble complexes with metal ions typically found in contaminated soils, which occurs over a wide range of pH values and conditions. Once complexed, the metal ions are immobilized and are unable to leach out beyond the phosphoric acid-treated soil. Heavy metal contaminants that are capable of phosphoric acid immobilization include: lead, strontium, zinc, cadmium, iron, chromium, and selenium. The use of this technology has been successful at various industrial sites, including metal mining, waste, ammunition, scrap metal, paint, and battery industries.

2.8.2 LCI Modeling

- Functional unit: 1 kg of phosphoric acid, fertilizer grade, 70% in H_2O .
- System boundaries: the production of phosphoric acid includes the mining and digestion of phosphate rock in sulfuric acid followed by filtration and concentration of the product (Althaus et al., 2007).

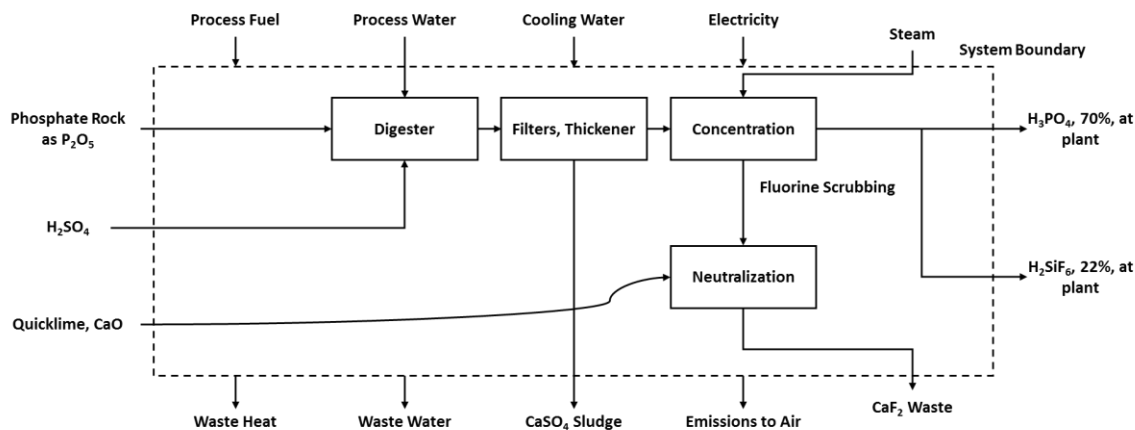


Figure 10. Production of phosphoric acid as shown in (Althaus et al., 2007).

- Inventory data: “phosphoric acid, fertilizer grade, 70% in H₂O, at plant – US”; ecoinvent 2.2; (Althaus et al., 2007).

2.8.3 Emission Factors

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM ₁₀ (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
Phosphoric Acid, 70% in water	6.70E-03	8.82E-01	1.63E-04	2.82E-03	1.71E-03	2.94E-02	1.61E+01

- Emission Factor Calculation Results.

Table 8. SEFA Emission Factors for Phosphoric Acid

2.9 Iron (II) Sulfate, Hydrated

2.9.1 Introduction

Iron (II) sulfate heptahydrate, ferrous sulfate, FeSO₄ • 7H₂O, crystallizes from an aqueous iron solution as green, monoclinic crystals that are readily soluble in water (Stolzenberg, 2000; Wildermuth et al., 2000). Most iron (II) sulfate is a by-product of the steel industry. Prior to tinning, galvanizing, electroplating, or enameling, steel surfaces are dipped in sulfuric acid for cleaning (pickling). The resulting pickle liquor contains ca 15% iron (II) sulfate and 2–7% acid. Scrap iron is added to reduce the acid concentration to ca 0.03%. The solution is filtered, concentrated at 70 °C to a specific gravity of 1.4, and allowed to cool to room temperature. The result is crystallization of the heptahydrate. Industry produces on the order of 10⁶ tons/yr. of the iron sulfate. Because supply exceeds demand, the pickling liquor presents a serious waste disposal problem. Iron(II) sulfate has a large variety of uses including iron oxide pigments and salts, fertilizer production, food and feed supplements, inks and dyes, reducing agents, polymerization catalysts, and water treatment. In water treatment, iron (II) sulfate is commonly used for municipal and industrial wastewater treatment as coagulants or flocculants, for odor control to minimize hydrogen sulfide release, for phosphorus removal, and as a sludge thickening, conditioning and dewatering agent.

2.9.2 LCI Modeling

- Functional unit: 1 lb. of Iron (II) sulfate heptahydrate.
- System boundaries: the production of iron (II) sulfate heptahydrate involves the dissolution of iron scrap in dilute sulfuric acid (Figure 11).

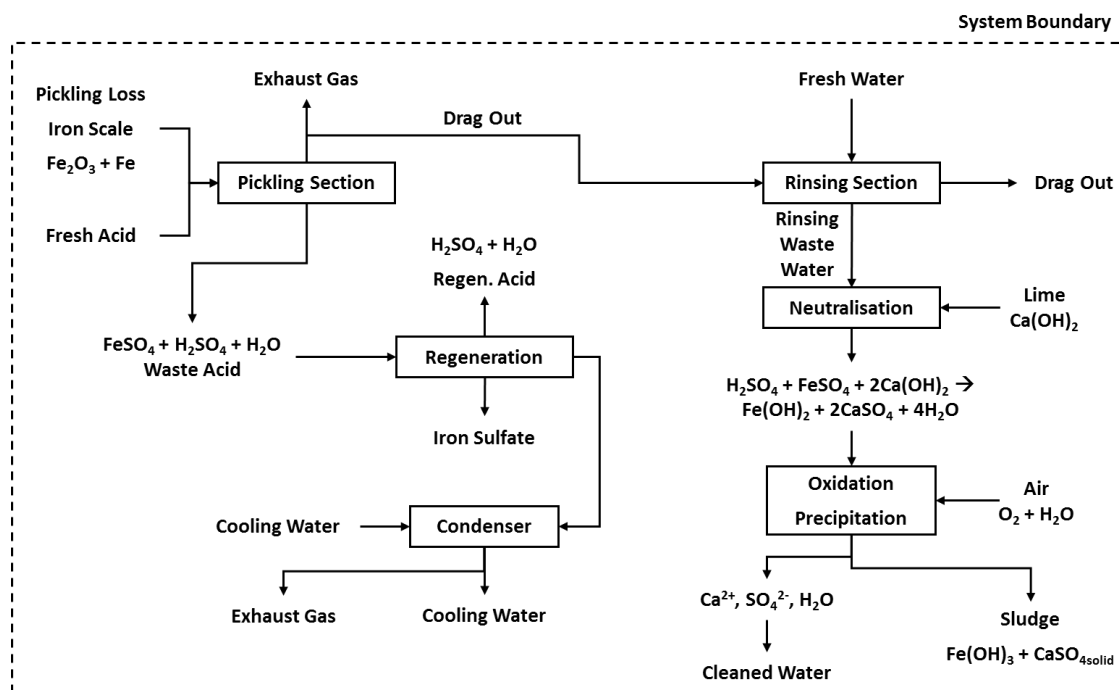


Figure 11. Production of iron (II) sulfate as shown in (EIPPCB, 2001)

- Inventory data: “iron sulphate, at plant - RER”; ecoinvent 2.2; (Jungbluth et al., 2007).

2.9.3 Emission Factors

- Emission Factor Calculation Results.

Table 9. SEFA Emission Factors for Hydrated Iron (II) Sulfate

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO2e/lb)	HAPs (lb/lb)	NOx (lb/lb)	PM10 (lb/lb)	SOx (lb/lb)	Water Use (gals/lb)
Iron (II) Sulfate, Hydrated	1.47E-03	1.67E-01	2.30E-05	3.16E-04	1.03E-04	5.89E-04	7.44E-01

2.10 Asphalt, Mastic-type and Pavement Grade

2.10.1 Introduction

Bitumen is a generic class of amorphous, dark colored, cementitious substances, composed principally of high molecular mass hydrocarbons, soluble in carbon disulfide, and is manufactured or natural occurring (ASTM, 2013c). Asphalt is defined as a cementitious material in which the

predominating constituents are bitumens. The terms bituminous and asphaltic then refer to materials that contain or are treated with bitumen or asphalt. Thus, some confusion exists, but in this report, asphalt and bitumen are used interchangeably.

Since the early 1900's most of the asphalts produced from the refining of petroleum have been used primarily in paving and roofing applications. Mastic asphalt has been used in some industrial applications. According to the International Mastic Asphalt Association (IMAA), mastic asphalt (MA) is a dense mass composed of a number of components, including: suitably graded mineral matter and/or sand, and/or limestone fine aggregate, and/or crushed limestone powder and bitumen, which may contain additives (for example polymers, waxes). The mixture is designed to be of low void content. The binder content is so adjusted the voids are completely filled and that even a slight excess of binder may occur.

In environmental applications, asphalt can be used as a barrier material. Prior to the mid1960's, asphalt barriers were primarily used to control water seepage from facilities such as impoundments and earth dams (Creegan & Monismith, 1996). For these applications, asphalt was applied as hot-sprayed asphalt membranes or as asphalt concrete for barrier layers. The petroleum shortage of the 1970's, along with the establishment of rules for hazardous and solid waste landfill designs, focused the industry toward composite liners consisting of geomembranes and compacted soil. However, in the mid-1980's, resurgence into the use of asphalt for waste isolation was initiated by the US Department of Energy (DOE) in their quest for very-long-term hydraulic barriers (1000+ years) for radioactive and mixed waste sites (Gee & Wing, 1993).

2.10.2 LCI Modeling – Mastic Asphalt

- Functional unit: 1 lb. of mastic asphalt
- System boundaries: the production of mastic involves the following inputs: bitumen, limestone powder, sand, infrastructure, and transport. Producing mastic outputs VOCs, benzopyrene, and waste heat (Figure 12).

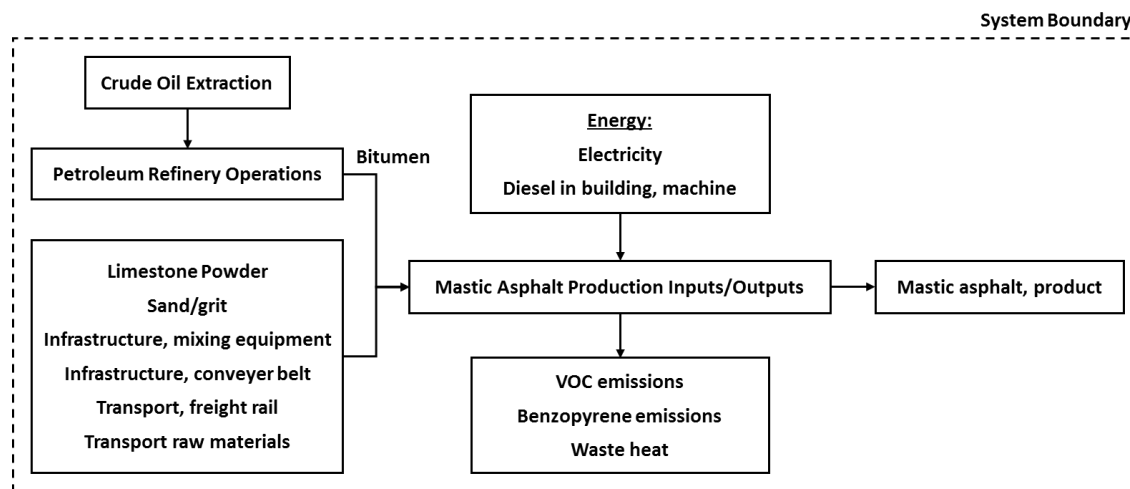


Figure 12. Production of mastic asphalt as shown in (Kellenberger et al., 2007)

- Inventory data: “mastic asphalt, at plant - RER”; ecoinvent 2.2; (Kellenberger 2007); process was modified by using the Eurobitume bitumen inventory in place of the ecoinvent bitumen inventory.

2.10.3 LCI Modeling – Pavement-grade Asphalt

- Functional unit: 1 lb. of pavement grade asphalt.
- System boundaries: producing pavement grade asphalt requires crude oil, which is transported, then refined and stored at a refinery (Figure 13).

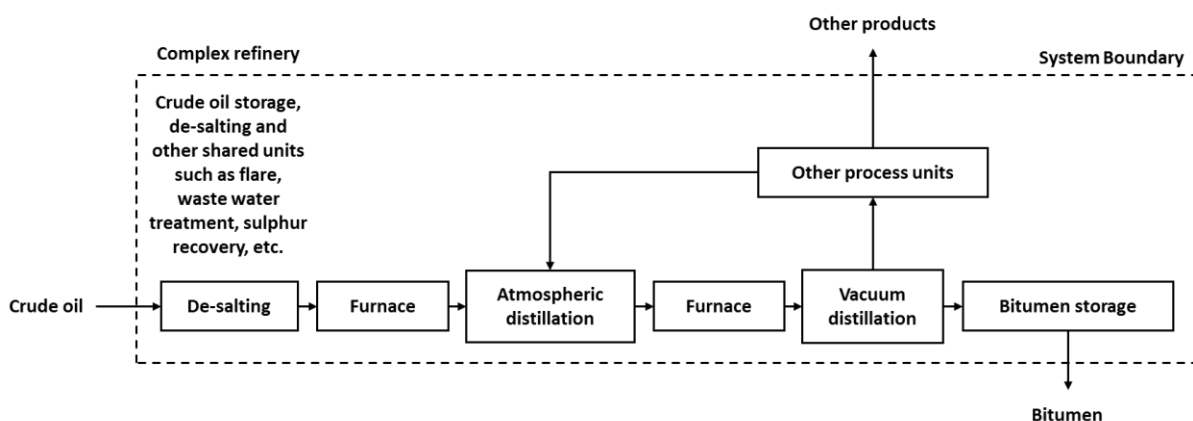


Figure 13. Bitumen production at a complex refinery as presented in (Eurobitume, 2012)

2.10.4 Emission Factors

- Emission Factor Calculation Results.

Table 10. SEFA Emission Factors for Mastic and Paving-Grade Asphalt

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM10 (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
Mastic Asphalt	4.12E-02	8.50E-01	1.07E-03	2.71E-03	7.66E-04	7.98E-03	5.46E-01
Paving Asphalt	5.00E-01	8.58E+00	1.33E-02	2.99E-02	9.10E-03	9.69E-02	3.88E+00

2.11 Aluminum, Rolled Sheet

2.11.1 Introduction

Aluminum is the third most abundant element in the earth’s crust and is usually found combined with silicon and oxygen in rock. When aluminum silicate minerals are subjected to tropical

weathering, aluminum hydroxide may be formed. Rock that contains high concentrations of aluminum hydroxide minerals is called bauxite (Frank et al., 2000; Sanders, 2012). Although bauxite is, with rare exception, the starting material for the production of aluminum, the industry generally refers to metallurgical grade alumina, Al_2O_3 , extracted from bauxite by the Bayer Process, as the ore. It takes roughly 4 – 7 tons of bauxite to produce 2 tons of alumina, which again yield 1 ton of aluminum (Norsk Hydro, 2012). Aluminum is obtained by electrolysis of this purified ore. The production of aluminum in the US is forecasted to total 7.1 million metric tons in 2017 (The Freedonia Group, 2013). According to USGS, world production in 2013 was 47.3 million metric tons (USGS, 2014).

Aluminum is a common piling material, where piling is a method of horizontal sealing to prevent the movement of groundwater. Aluminum pile enclosures minimize or eliminate the need for contaminant plume control by groundwater pumping and/or water treatment. Contaminants are prevented from moving off site, while site control activities (e.g., source removal, plume remediation) are carried out in the isolated subsurface environment inside the piled enclosure.

2.11.2 LCI Modeling

- Functional unit: 1 lb. of rolled aluminum.
- System boundaries: Figure 14 is the system boundary for the extraction of bauxite to the production of primary Aluminum ingots to Aluminum sheets. Several processes lead to the production of primary aluminum, including bauxite mining, alumina extraction, production of other raw materials, and anode fabrication. Following primary aluminum production, the aluminum is sawed, scalped, rolled, and then heat-treated. Once heat-treated, the aluminum is finished, packaged, used, collected, sorted, and then recycled with associated metal losses.

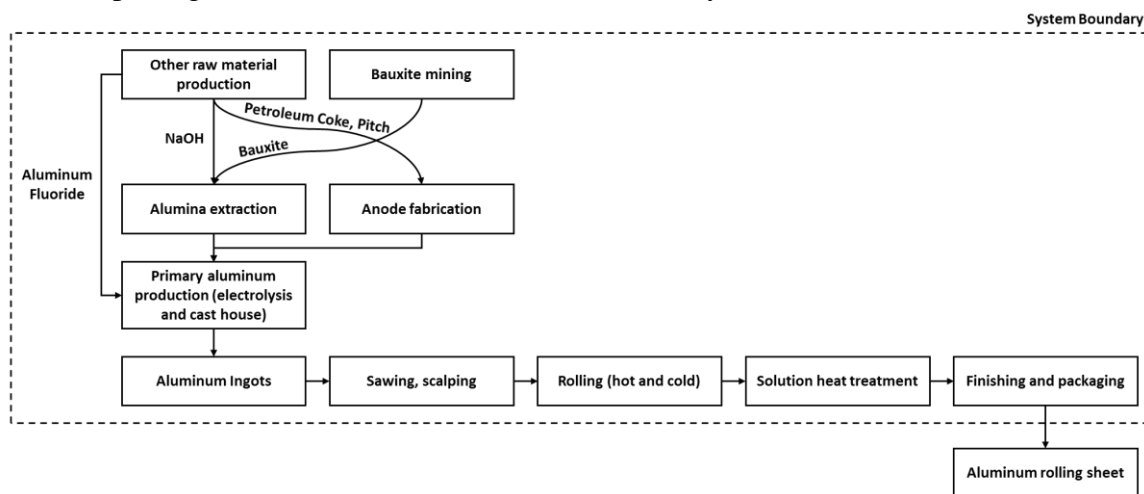


Figure 14. System Boundary-Production of Aluminum as adapted by (EAA, 2013) and (Classen et al., 2007)

- Inventory data: “aluminum, primary, at plant - RER”; ecoinvent 2.2; (Althaus et al., 2007); “anodizing, aluminum sheet - RER”; ecoinvent 2.2; (Classen et al., 2007); “sheet rolling, aluminum - RER”; ecoinvent 2.2; (Werner, Althaus, Künniger, Richter, & Jungbluth, 2007).

2.11.3 Emission Factors

- Emission Factor Calculation Results.

Table 11. SEFA Emission Factors for Rolled Aluminum

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM10 (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
Aluminum, Rolled Sheet	6.33E-02	9.15E+00	1.02E-03	1.48E-02	8.80E-03	2.83E-02	2.78E+01

2.12 Granular Activated Carbon (GAC), Primary and Regenerated

2.12.1 Introduction

Granular activated carbon (GAC) is a carbonaceous material used to remove various contaminants through adsorption from either liquid or gas streams. The most common precursor materials for GAC are bituminous coal, lignite coal, coconut shells, and wood.

Commercial production of activated carbon is a two-step process involving carbonization of a precursor material followed by activation. In the pyrolytic carbonization process, the temperature of the raw material is raised to the range of 500 to 800 °C in the absence of oxygen. Volatile organic matter of the raw material is thermally released, and the carbon atoms realign to form a crystalline structure. The carbonized product at this point in the process is heavily influenced by the raw materials used. For activated carbon products used in water treatment, a thermal or physical activation process follows in which the temperature of the carbonized product is increased to the range of 850 to 1,000 °C in the presence of an oxidizing agent, typically steam or carbon dioxide. Activation increases the pore sizes and creates a continuous pore structure, which increases the micropore volume (pore width < 2 nm) and the internal surface area where most of the adsorption occurs. The activation step can involve either a direct activation process in which the raw material is crushed and then activated, or in a reagglomeration process in which the raw material is crushed, reagglomerated, crushed again, and then activated.

Reactivation of spent activated carbon involves the destruction of contaminants and the reactivation of useful carbon. Contaminants are desorbed and destroyed at high temperatures (typically exceeding 1500 °F) in a reactivation furnace. Furnaces can either be rotary kilns or multiple hearths, and can be heated by either natural gas, electricity, or fuel oil. Off-site carbon reactivation manufacturers reactivate anywhere from 5 to 60 tons of spent carbon on a daily basis. While larger-capacity furnaces are not typically cost-effective for a single hazardous waste site, smaller furnaces are more cost-effective for on-site use at a single site. Reactivation furnaces output reactivated carbon, air emissions, and some carbon fines. Reactivation furnaces do not produce organic wastes.

2.12.2 LCI Modeling

- Functional unit: 1 lb. of granular activated carbon (primary or regenerated).
- System boundaries: for primary GAC, the modeled process includes the extraction and conversion of coal using pyrolytic carbonization and thermal activation (Figure 15). Regenerated GAC includes thermal desorption and reactivation of captured contaminants (Figure 16). Data describing emission profiles during regeneration could not be obtained.

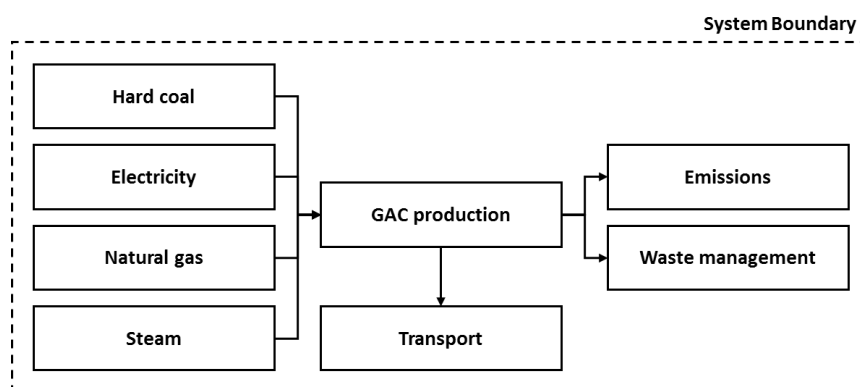


Figure 15. System boundary for primary GAC as adapted from (Gabarrell et al., 2012)

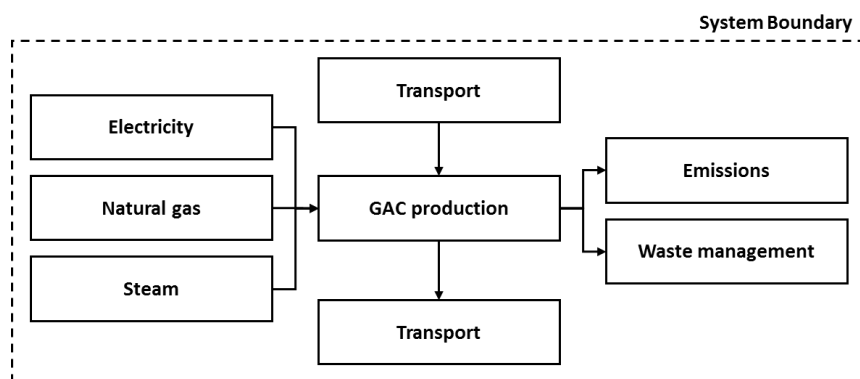


Figure 16. System boundary for regenerated GAC as adapted from (Gabarrell et al., 2012)

Inventories from (USEPA, 2010a) and (He, 2012) were created separately in openLCA and analyzed using the footprint method. The resulting EmFs were arithmetically averaged to create the reported EmFs in Section 2.12.3.

2.12.3 Emission Factors

□ Emission Factor Calculation Results.

Table 12. SEFA Emission Factors for Primary and Regenerated Granular Activated Carbon

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM10 (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
Primary Activated Carbon	3.56E-02	4.82E+00	6.57E-04	7.93E-02	9.87E-04	1.28E-01	1.53E+00
Regenerated Activated Carbon	8.73E-03	1.70E+00	6.71E-04	7.33E-03	8.86E-04	1.29E-02	1.20E+00

2.13 Portland Cement

2.13.1 Introduction

Portland cement is the most common type of cement used globally. It is the hydraulic binder in concrete and mortar. Portland cement is made by heating limestone (i.e., calcium carbonate) with other materials (e.g., clay) in a 1450 °C kiln. This process is known as calcination, where a molecule of CO₂ is liberated from the calcium carbonate to form calcium oxide, which is then mixed with the other materials to form calcium silicates and other cementitious compounds. The resulting hard substance, clinker, is ground with gypsum into a powder to make ordinary Portland cement (OPC).

Cement is primarily used as a constituent of concrete, and concrete has a number of remediation site applications. The most common concrete application at remediation sites is in the form of buildings and foundations. Its use is not limited to remediation sites, and concrete is extensively used to form building walls, foundations, and other elements within a building.

2.13.2 LCI Modeling

- Functional unit: 1 lb. of Portland cement.
- System boundaries: the production of Portland cement includes rock quarrying and crushing; raw meal preparation through grinding and blending; calcination of rock and mix components to form clinker, and final grinding and bagging (Figure 17).

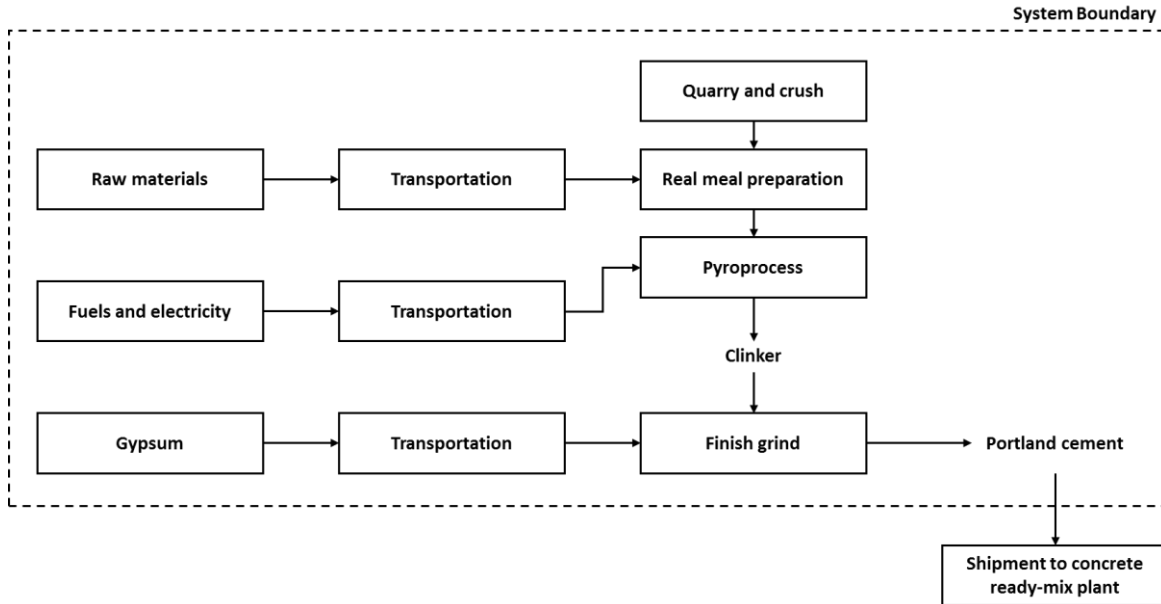


Figure 17. Production of Portland cement as reported by (Marceau, Nisbet, & Van Geem, 2006)

2.13.3 Emission Factors

□ Emission Factor Calculation Results.

Table 13. SEFA Emission Factors for Portland cement

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM10 (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
Portland Cement	1.39E-02	1.34E+00	9.70E-04	6.54E-03	3.78E-03	1.04E-02	7.73E-01

2.14 Ready Mixed Concrete (20 MPa-3000psi)

2.14.1 Introduction

Concrete is a high-volume, low-cost building material produced by mixing cement, water, and aggregates. The use of concrete is nearly universal in modern construction, where it is an essential component of high-rise buildings, pavement, bridges, dams, buildings, and other staples of the developed landscape. There are thousands of possible ready mixed concrete (RMC) products (a.k.a. mix designs, mixes, mixture compositions or mixtures), which ultimately balance the cost and performance of concrete for a wide variety of applications. There are many factors that can influence the way concrete is manufactured, designed, built, used, and recycled that ultimately affect the environmental footprint of concrete and the structures built with concrete. Several factors that can affect the environmental performance of concrete and concrete structures include: design

loads, structural efficiency, durability, constructability, energy efficiency, aesthetics, and concrete mixtures.

2.14.2 LCI Modeling

- Functional unit: 1 cubic foot of ready-mixed concrete.
- System boundaries: the production of ready-mixed concrete includes the preparation of Portland cement (Section 2.13) and mixing it with aggregates and water to form concrete (Figure 18).

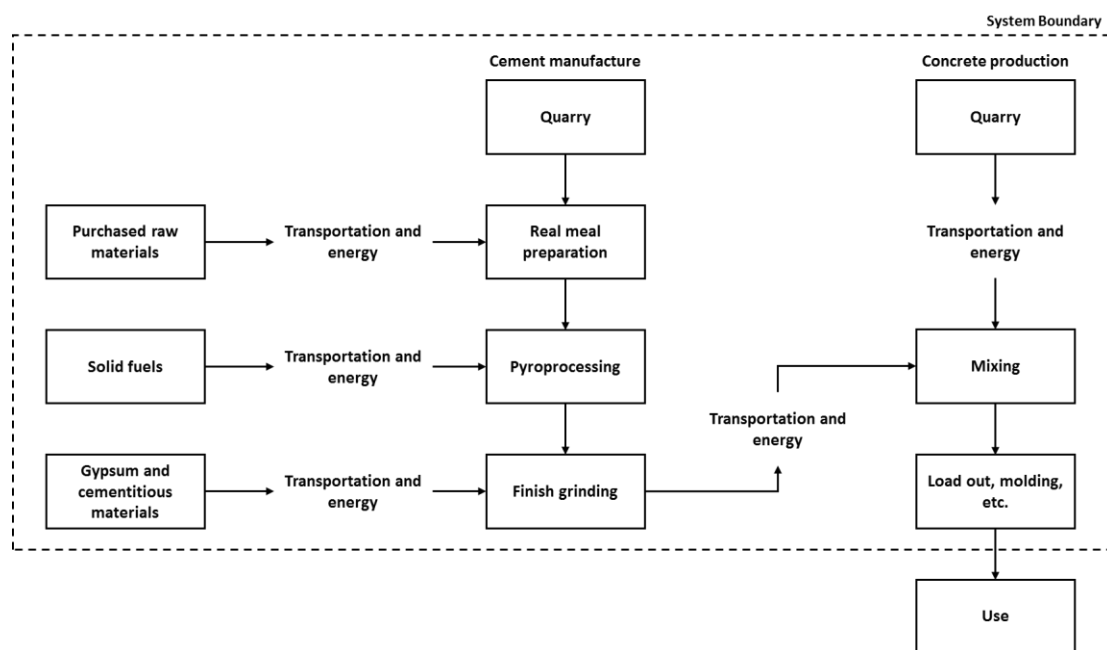


Figure 18. Production of ready mixed concrete as reported by (Nisbet, 2000)

2.14.3 Emission Factors

□ Emission Factor Calculation Results.

Table 14. SEFA Emission Factors for Ready Mixed Concrete

Chemical/Material	CED (MMBtu/ft ³)	GWP100 (lb CO ₂ e/ft ³)	HAPs (lb/ft ³)	NO _x (lb/ft ³)	PM10 (lb/ft ³)	SO _x (lb/ft ³)	Water Use (gals/ft ³)
Ready Mixed Concrete	2.17E-01	1.95E+01	1.41E-02	9.75E-02	5.70E-02	1.54E-01	3.32E+01

2.15 Gravel and Sand Mix, 65% Gravel

2.15.1 Introduction

Construction aggregates find use in a wide range of applications including road base and coverings, hydraulic concrete, asphaltic concrete, foundation fill, railroad ballast, roofing granules, and snow and ice control. The primary function for road base and subbase aggregates is to provide a solid, sturdy foundation for driving surfaces. A wide range of items (including natural aggregates and alternative, secondary, and recycled materials) comprises the segment and product specifications are generally less restrictive than other applications. Natural aggregates consist of crushed stone, sand, and gravel obtained from quarries. Natural aggregates are among the most abundant natural resources and a major basic raw material used by construction, agriculture, and industries employing complex chemical and metallurgical processes. Gravel and sand are used at remediation sites through several applications. Crushed stone (i.e., gravel) can be used in temporary roads at remediation sites. Temporary gravel roads provide periodic access points for remediation site employees, and are able to be removed and disposed once their useful life is reached (USEPA, 1996). Gravel and sand are important constituents in geomembranes used as vertical barriers to prevent the spread of contaminated groundwater. A 1994 study by Burnette and Schmednecht focused on a geomembrane cutoff wall that encompassed a Great Lakes chemical plant, which consisted of layers of sand, gravel, and cobbles (Brunette & Schmednecht, 1994).

2.15.2 LCI Modeling

Note: round gravel and sand are produced simultaneously in a quarry. As such, they are modeled as co-products of the same unit process in ecoinvent. The mixture here represents a typical blend for construction use and is modeled as 65% gravel 35% sand. The same process description and boundaries apply for the sand, gravel, and mixture processes. No allocation is applied to the ecoinvent process and both products receive identical impacts. Therefore, the emission factors reported in Table 15 apply to 1 lb. of sand, 1 lb. of round gravel, or 1 lb. of a gravel/sand mix as listed in the table. The consequence of this approach is the impacts for the mixture are not a function of the composition.

- Functional unit: 1 lb. of a sand/gravel mix.
- System boundaries: the system boundary for producing a gravel and sand mix includes processes related to the extraction of round gravel and sand (i.e., no crushed gravel) at a quarry, internal processes (i.e., transport, etc.), and infrastructure for the operation (i.e., machinery) (Figure 19).

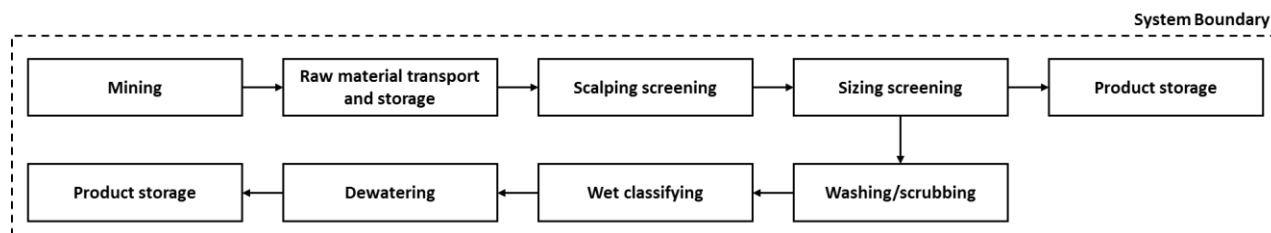


Figure 19. Typical production of sand and gravel as reported by (USEPA, 1995a)

- Inventory data: 0.65 lbs. of “gravel, round, at mine – CH”, ecoinvent 2.2; (Kellenberger et al., 2007); 0.35 lbs. of “sand, at mine – CH”, ecoinvent 2.2; (Kellenberger et al., 2007).

2.15.2 Emission Factors

- Emission Factor Calculation Results.

Table 15. SEFA Emission Factors for a Gravel, Sand, or a Gravel/Sand Mix

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM10 (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
Gravel, Sand, or Gravel/Sand Mix	2.48E-05	2.40E-03	3.08E-07	1.80E-05	2.61E-06	4.52E-06	1.71E-01

2.16 High Density Polyethylene (HDPE)

2.16.1 Introduction

Because of its versatility, HDPE is one of the most popular plastics in use today, with a projected global market of almost \$70 billion by 2019 (Plastic News, 2013). HDPE resin is used in many applications, including industrial wrappings and films, crates, boxes, caps and closures, bottles and containers for food products, cosmetics, pharmaceuticals, household and industrial chemicals, toys, fuel tanks and other automotive parts, and pipes for gas and water distribution.

HDPE can be used as panels constituting vertical barrier systems in order to remediate polluted groundwater systems. For example, a 1997 case study focused on using HDPE panels as a remediation technique for a waterway seeping, dense, non-aqueous phase, liquids (DNAPLs). The study found advantages of using HDPE vertical barrier systems include: flexibility, low permeability rates (e.g., 2.7×10^{-13} cm/s), resistant to a variety of chemicals, long service life, quick installation, and low economic costs (Burson, Baker, Jones, & Shailer, 1997). HDPE has been shown to be a suitable flexible membrane liner (FML) at landfill sites. HDPE geomembranes are extremely resistant to leachates, which is a primary factor influencing the use of HDPE in FMLs (Eithe & Koerner, 1997).

HDPE is a polyolefin produced from the polymerization of ethylene. The polymer properties can be controlled and varied by adding co-monomers such as butene or hexene to the blend. The

manufacturing of HDPE starts with applying heat to petroleum (i.e., cracking), which produces ethylene gas. Under controlled conditions the ethylene gas molecules link together to form long chains (or polymers), thus producing polyethylene. The reaction occurs in a large loop reactor with the mixture being constantly stirred. Upon opening a valve, the product is released, and the solvent evaporated, leaving the polymer and catalyst. Water vapor and nitrogen are reacted with the polymer to cease catalytic activity. Residues of the catalyst, which are typically titanium (IV) and aluminum oxides, remain mixed in the polymer. The HDPE powder produced from the reactor is separated from the diluent or solvent (if used) and is extruded and cut up into granules.

2.16.2 LCI Modeling

- Functional unit: 1 lb. of high-density polyethylene, granulate type.
- System boundaries: the production of HDPE includes the upstream extraction and processing of crude oil to make ethylene; the blending of ethylene with co-monomers, solvents, and additives; catalyzed polymerization of the mixture to form HDPE; and finishing producing HDPE resin (Figure 20). The impacts of downstream processing of HDPE resin to form product(s) used at remediation sites is assumed to be negligible compared to the included processes.

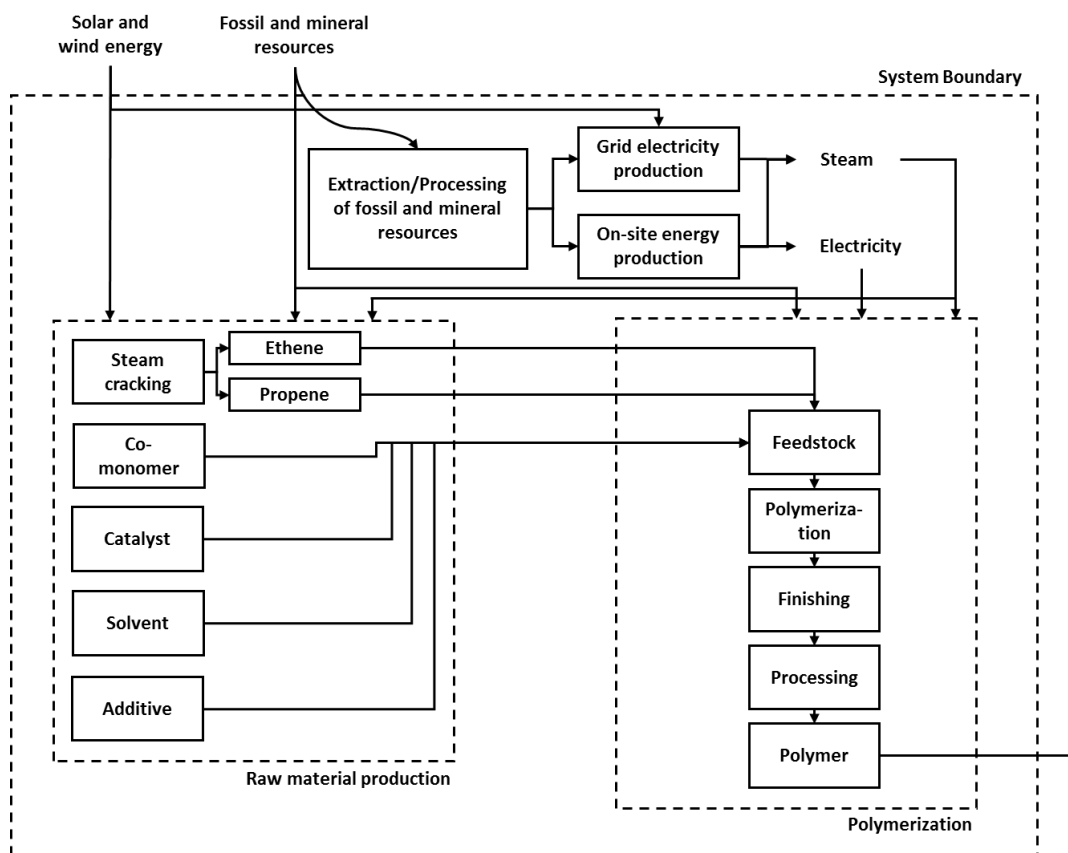


Figure 20. Production of High Density Polyethylene as reported by (PlasticsEurope, 2014)

- Inventory data: “polyethylene, HDPE, granulate, at plant- RER”; ecoinvent 2.2; (Hischier, 2007).

2.16.3 Emission Factors

- Emission Factor Calculation Results.

Table 16. SEFA Emission Factors for High Density Polyethylene

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM10 (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
High Density Polyethylene	3.32E-02	1.94E+00	6.41E-05	3.25E-03	4.39E-04	4.09E-03	3.88E+00

2.17 Polyvinyl Chloride (PVC)

2.17.1 Introduction

Polyvinyl chloride (PVC) is, the third largest, by volume, thermoplastic manufactured in the world. PVC is a key product of the chemical industry and, along with polypropylene and polyethylene, one of the most widely produced plastics. PVC use is highly dependent on the construction market, as about 70% of its world consumption is for pipe, fittings, siding, windows, fencing, electrical and other applications. At remediation sites, PVC is used for well casings, piping, cutoff walls, geomembranes, liners, and cap (USEPA, 2012a).

There are three main processes used for the commercial production of PVC: suspension (providing 80% of world production), emulsion (12%) and mass (also called bulk) (8%) (Fischer, Schmitt, Porth, Allsopp, & Vianello, 2014). The first step of suspension PVC manufacturing is feeding vinyl chloride monomer (VCM) into a polymerization reactor with water and suspending agents. High-speed agitation forms small droplets of VCM, which are then introduced to a catalyst. PVC is obtained by way of the catalyst, pressure, and temperatures ranging from 40 to 60°C. The slurry discharged from the polymerization reactor is stripped of un-reacted VCM, and dried by centrifugation. The result is PVC in the form of white powder, or resin. Emulsion polymerization is a far less common technology to manufacture PVC. Emulsion polymerization produces finer resin grades with much smaller particles, which are required by certain applications. Emulsion polymerization takes place in pressurized vessels under the influence of heat and catalysts. Polymerization occurs within the dispersed VCM droplets and with an initiator that is highly soluble in VCM (not water). The product is transferred to a blow-down vessel, where the unreacted monomer is extracted, recovered, and recycled back to the polymerization reactor. The polymer particles are then dried.

2.17.2 LCI Modeling

- Functional unit: 1 lb. of polyvinyl chloride.
- System boundaries: typical production of PVC includes the upstream production of ethylene from crude oil, and chlorine from brine and rock salt; the chlorination of ethylene to yield vinyl chloride; the polymerization of vinyl chloride to make PVC resin; and the transport of the resin to a regional storehouse for distribution and downstream use (Figure 21). As with HDPE, further processing of resin to products for use onsite during remediation is assumed negligible.

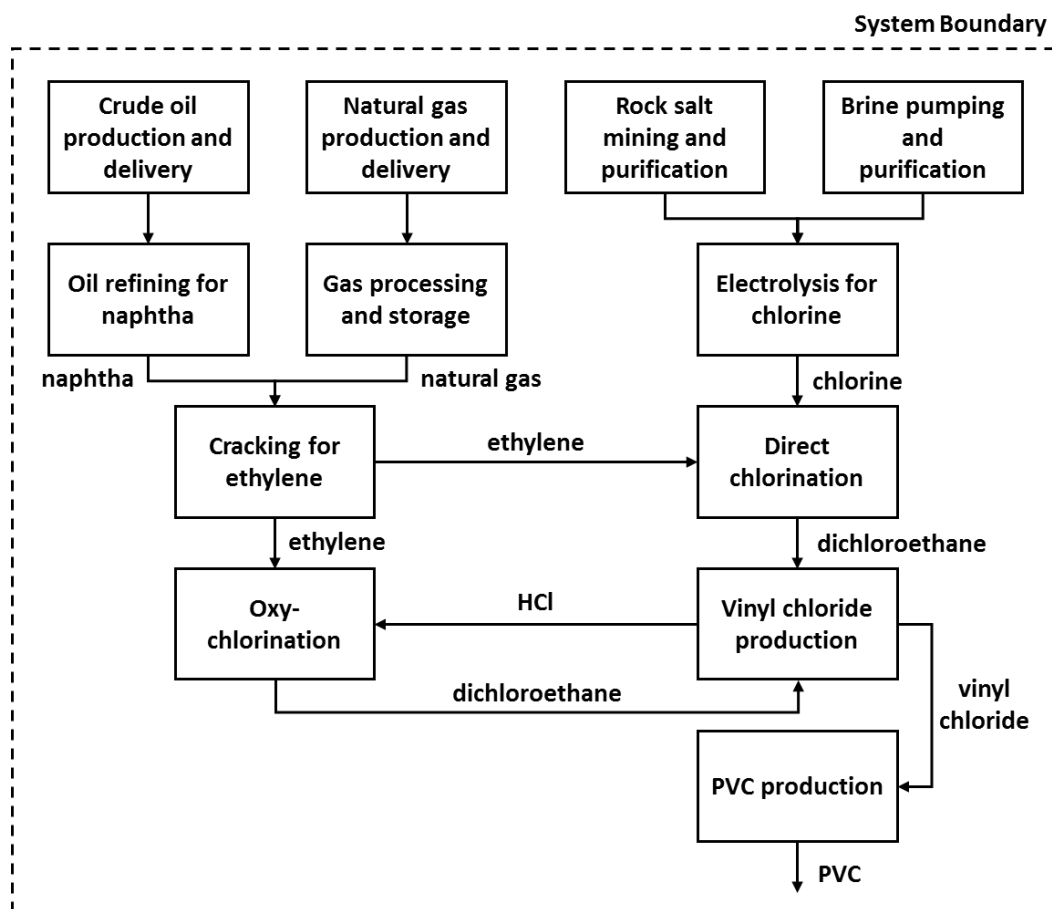


Figure 21. Flow Diagram for the Cradle to Gate Production of PVC as reported by (Hischier, 2007)

- Inventory data: “polyvinylchloride, at regional storehouse - RER”, ecoinvent 2.2; (Hischier, 2007); The cited process assumes 87% resin production from the suspension method and 13% from the emulsion method.

2.17.3 Emission Factors

- Emission Factor Calculation Results.

Table 17. SEFA Emission Factors for Polyvinyl Chloride

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM10 (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
Polyvinyl Chloride	2.62E-02	2.02E+00	3.75E-04	4.00E-03	3.72E-04	2.74E-03	5.79E+01

2.18 Hazardous Waste Incineration

2.18.1 Introduction

The hazardous waste management market reached \$23.8 billion in 2013 and \$25.9 billion in 2014, global, and will continue to grow steadily and expected to reach \$33.9 billion by the end of 2019 (BCC Research, 2015). Over the last five years, the quantities of hazardous waste generated in North America varied between 150.0 million and 170.0 million metric tons in 2012. Hazardous waste is expected to increase consistently in the years to come mainly due to increasing industrial productivity.

Incineration is the most commonly used method for thermal treatment of organic liquids, solids, and sludge contaminated with toxic organics. During incineration, high temperatures between 871°C and 1204°C (1600°F and 2200°F) are used to combust (in the presence of oxygen) the organic constituents in hazardous wastes. Incinerators are usually classified by the type of combustion unit, with rotary kiln, liquid injection, fluidized bed, and infrared units being those most commonly used for hazardous wastes. Existing industrial boilers and kilns, especially cement kilns, are sometimes used for thermal treatment of hazardous wastes.

2.18.2 LCI Modeling

- Functional unit: 1 lb. of incinerated hazardous waste.
- System boundaries: hazardous waste incineration involves the following steps: (1) hazardous waste processing (which includes screening, size reduction, and waste mixing); (2) combustion; (3) air pollution control (measurement to collect or treat products of incomplete combustion, particulate emissions, and acid gases); and (4) solids removal and disposal (Figure 22).

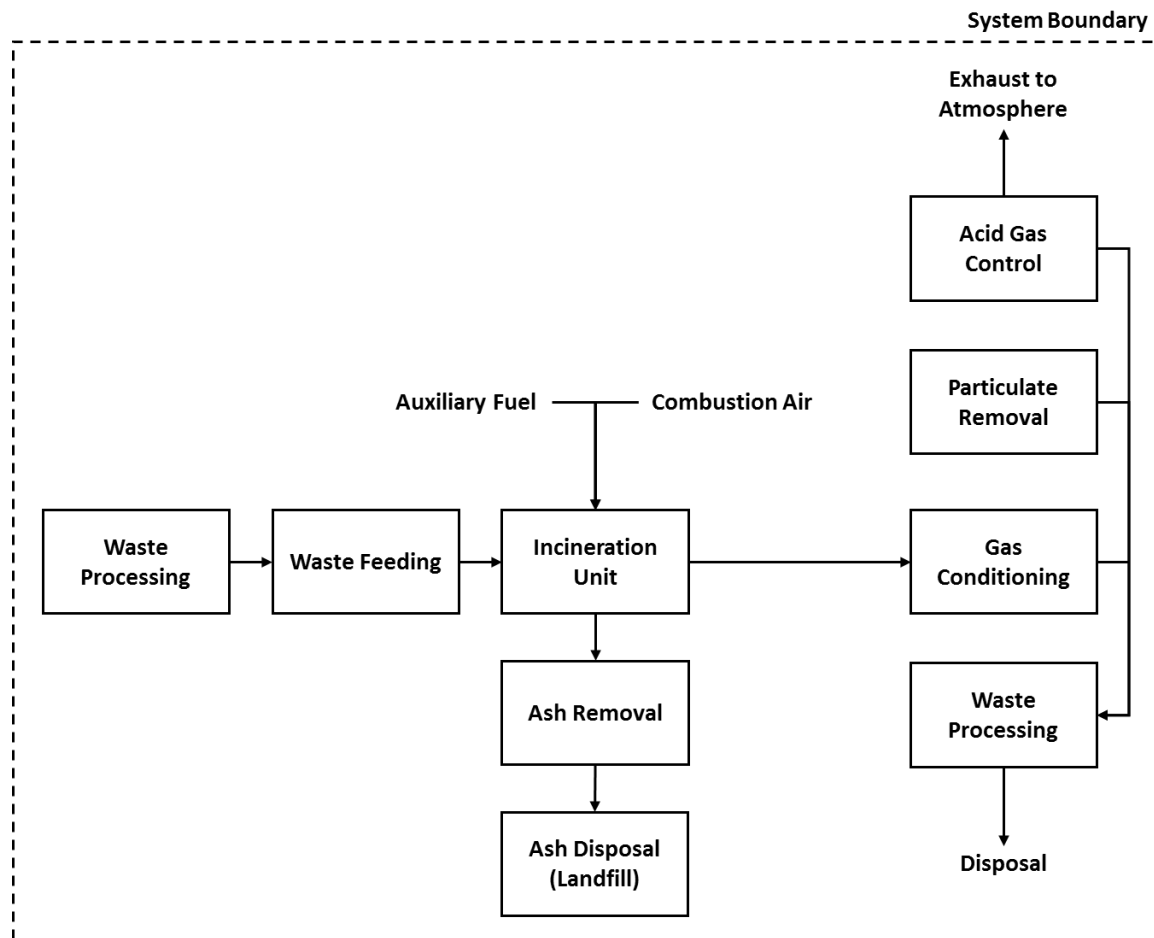


Figure 22. Simplified Diagram of Hazardous Waste Incineration as reported by (BCC Research, 2015)

- Inventory data: “disposal, hazardous waste, 25% water, to hazardous waste incineration – CH”, ecoinvent 2.2; (Doka, 2009).

2.18.3 Emission Factors

- Emission Factor Calculation Results.

Table 18. SEFA Emission Factors for Hazardous Waste Incineration

Chemical/Material	CED (MMBtu/lb)	GWP100 (lb CO ₂ e/lb)	HAPs (lb/lb)	NO _x (lb/lb)	PM10 (lb/lb)	SO _x (lb/lb)	Water Use (gals/lb)
Hazardous Waste Incineration	6.09E-03	2.43E+00	8.70E-05	1.60E-03	2.09E-04	1.67E-03	3.77E+00

2.19 SEFA Material Emission Factor Update Summary

Table 19. A Summary of Emission Factors Derived for the SEFA Material Update

Chemical/Material/Process	Unit	Energy Used MMBtu	GHGs Emitted lb CO ₂ e	HAPs Emitted lb	NO _x Emitted lb	PM ₁₀ Emitted lb	SO _x Emitted lb	Water Used gals	Source(s)
Aluminum, Rolled Sheet	lb	6.33E-02	9.15E+00	1.02E-03	1.48E-02	8.80E-03	2.83E-02	2.78E+01	(Classen, Althaus et al. 2009)
Asphalt, mastic	lb	4.12E-02	8.50E-01	1.07E-03	2.71E-03	7.66E-04	7.98E-03	5.46E-01	(Jungbluth, Chudacoff et al. 2007)
Asphalt, paving-grade	lb	5.00E-01	8.58E+00	1.33E-02	2.99E-02	9.10E-03	9.69E-02	3.88E+00	(Jungbluth, Chudacoff et al. 2007)
Ethanol, Corn, 95%	lb	3.18E-02	-1.99E-02	8.46E-05	4.25E-03	4.69E-04	3.03E-03	4.32E+00	(Kellenberger, Althaus et al. 2007)
Ethanol, Corn, 99.7%	lb	3.24E-02	5.91E-02	8.70E-05	4.31E-03	4.72E-04	3.10E-03	4.35E+00	(Doka 2009)
Ethanol, Petroleum, 99.7%	lb	2.05E-02	1.25E+00	5.89E-05	1.99E-03	2.77E-04	2.14E-03	4.16E+00	(Hischier 2007; PlasticsEurope 2014)
Granular activated carbon, primary	lb	3.56E-02	4.82E+00	6.57E-04	7.93E-02	9.87E-04	1.28E-01	1.53E+00	(USEPA 2010)
Granular activated carbon, regenerated	lb	8.73E-03	1.70E+00	6.71E-04	7.33E-03	8.86E-04	1.29E-02	1.20E+00	(USEPA 2010; He 2012)
Gravel/Sand Mix, 65% Gravel	lb	2.48E-05	2.40E-03	3.08E-07	1.80E-05	2.61E-06	4.52E-06	1.71E-01	(Kellenberger, Althaus et al. 2007)
Hazardous Waste Incineration	lb	6.09E-03	2.43E+00	8.70E-05	1.60E-03	2.09E-04	1.67E-03	3.77E+00	(Kellenberger, Althaus et al. 2007)
High Density Polyethylene	lb	3.32E-02	1.94E+00	6.41E-05	3.25E-03	4.39E-04	4.09E-03	3.88E+00	(Eurobitume 2012; Athena 2005)
Hydrogen Peroxide, 50% in H ₂ O	lb	9.79E-03	1.19E+00	6.29E-05	1.42E-03	3.08E-04	2.40E-03	2.35E+01	(Sutter 2007)
Iron (II) Sulfate	lb	1.47E-03	1.67E-01	2.30E-05	3.16E-04	1.03E-04	5.89E-04	7.44E-01	(Althaus, Chudacoff et al. 2007)
Lime, Hydrated, Packed	lb	2.06E-03	7.62E-01	6.57E-06	5.13E-04	1.30E-04	3.58E-04	2.94E-01	(Hischier 2007; PlasticsEurope 2015)
Phosphoric Acid, 70% in H ₂ O	lb	6.70E-03	8.82E-01	1.63E-04	2.82E-03	1.71E-03	2.94E-02	1.61E+01	(Marceau, Nisbet et al. 2006)
Polyvinyl Chloride	lb	2.62E-02	2.02E+00	3.75E-04	4.00E-03	3.72E-04	2.74E-03	5.79E+01	(Classen, Althaus et al. 2009)
Portland cement, US average	lb	1.39E-02	1.34E+00	9.70E-04	6.54E-03	3.78E-03	1.04E-02	7.73E-01	(Bhargava and Sirabian 2013; He 2012; USEPA 2010)
Potassium Permanganate	lb	9.81E-03	1.16E+00	1.22E-04	2.34E-03	4.22E-04	3.20E-03	7.45E+00	(Marceau, Nisbet et al. 2006)
Ready-mixed concrete, 20 MPa	ft ³	2.17E-01	1.95E+01	1.41E-02	9.75E-02	5.70E-02	1.54E-01	3.32E+01	(Bhargava and Sirabian 2013; He 2012; USEPA 2010)
Round Gravel	lb	2.48E-05	2.40E-03	3.08E-07	1.80E-05	2.61E-06	4.52E-06	1.71E-01	(Kellenberger, Althaus et al. 2007)
Sand	lb	2.48E-05	2.40E-03	3.08E-07	1.80E-05	2.61E-06	4.52E-06	1.71E-01	(Kellenberger, Althaus et al. 2007)
Sodium Hydroxide, 50% in H ₂ O	lb	9.77E-03	1.09E+00	1.29E-04	1.94E-03	4.03E-04	3.52E-03	1.39E+01	(Althaus, Chudacoff et al. 2007)

3.0 Transportation and Onsite Equipment

3.1 Methodology

Emissions and activity factors were created by developing life cycle models that combined data from a variety of sources. Emission factors are in the form of emissions or energy use per gallon fuel consumed. The activity factors are used to relate fuel consumption to equipment or vehicle activity, and are in the form of activity per gallon fuel (e.g., hp-hr./gallon for on-site equipment). The SEFA project team in Region 9 and OSWER specified the designation of equipment and vehicle classes for which factors are provided.

The overall workflow for the calculation of the emission and activity factors is summarized in Figure 23. Details are described in the following sections.

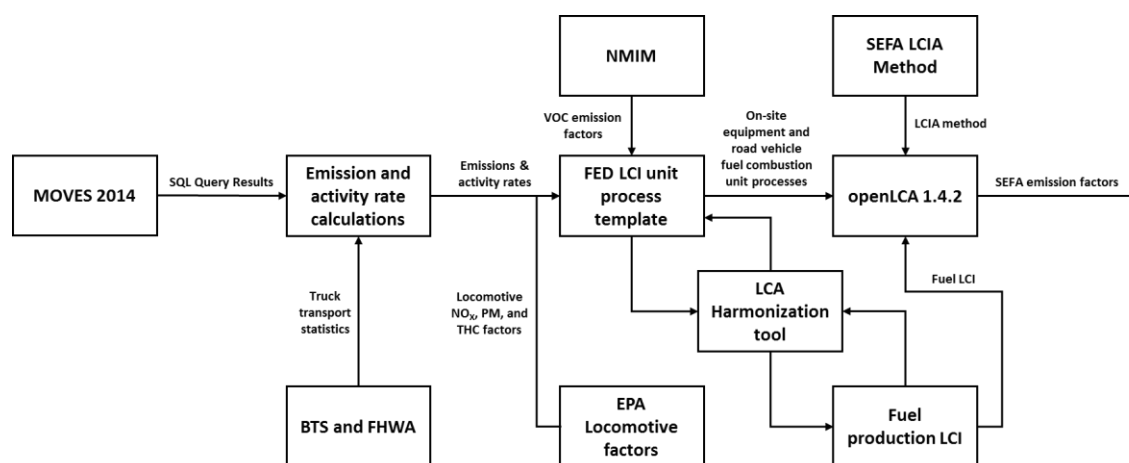


Figure 23. Workflow for SEFA emission and activity factor calculations.

3.1.1 Fuel Production and Distribution Data

A petroleum refinery and distribution model developed within EPA ORD's National Risk Management Research Laboratory (NRMRL) and described in (Sengupta, Hawkins, & Smith, 2015), was used as the primary source of data for developing emissions factors for conventional diesel, gasoline, and LPG, which are all petroleum refinery co-products. This model includes a unique petroleum refinery process model based on national average emissions data. Original US data for distribution to a storage terminal and final dispensing station are included. These data are supplemented by upstream processes from United States Life Cycle Inventory (USLCI) (NREL, 2008) for crude oil extraction and processes for other materials and infrastructure from the Ecoinvent 2.2 (B. Weidema & Hirschier, 2012) databases. Electricity used at the refinery is based on another NRMRL LCI model described in Ingwersen, Gausman et al. (Wesley Ingwersen et al., 2016). For compressed natural gas (CNG) fuels, which are not sourced from petroleum, we used USLCI natural gas processes to describe natural gas production and refining and estimated electricity consumption required to compress the gas. CNG compression energy was assumed to

be 2% of the inherent energy content of the fuel and electricity was assumed to be the energy source (Sinor, 1992). The CNG and LPG processes do not include transportation processes between manufacturer and point-of-sale, but based on analysis of petroleum life cycles, these stages are not expected to play a significant role in life cycle emissions (Vineyard & Ingwersen, 2015), so the expected effects on results are negligible.

3.1.2 MOVES Model Runs for On-site Equipment and Transport Data

Data for creating the on-site equipment and transportation were derived primarily from the Motor Vehicle Emission Simulator (MOVES) model (USEPA, 2014c); a model constructed and maintained by EPA's Office of Transportation and Air Quality. MOVES runs were performed to gather data on projected emissions for the average fleet performance for 2015, both in onroad and nonroad (on-site) applications. A MOVES RunSpec was set up to specify application type (onroad/nonroad), vehicle class (vehicle weight and fuel type) for onroad or engine specifications (equipment category, fuel type, horsepower, number of strokes) for nonroad, calculation type (inventory/emission rate), geographic scale, time scale, source use, and data aggregation options (see Supporting Data). The onroad runs were set to aggregate emissions quantities annually on a national scale for the year 2015. Nonroad runs in MOVES 2014 are based on the incorporation of a limited version of EPA NONROAD 2008 model that only calculates emissions on a per day basis. For onroad, personal transport vehicles were captured in one run, which included all passenger cars and passenger trucks using gasoline or diesel fuel. Light commercial trucks were in a separate run, but were used to represent the LHD and MHD diesel pickup trucks used for personal transport. Additionally, there were runs for heavy-duty trucks (combination and single-unit trucks). The nonroad emissions were generated using a single MOVES NONROAD run for typical equipment in the Construction and Industrial categories.

The output tables for MOVES simulations were generated as MySQL databases, from which desired data were extracted using MySQL queries. The MOVES output contained emission data described with a series of identification codes for such things as pollutant type, equipment classification, day of the week, and month of the year. As part of the querying process, identification coding data from a run output table were used to extract corresponding descriptors from the default MOVES 2014 input tables so that a custom output table could be created that displayed quantities and names instead of ID numbers. Output of queries were saved as CSV files and imported into a spreadsheet where they were further processed and aggregated.

Given the nonroad runs generated emissions in terms of a typical weekday or weekend within each month of the year, annual emission quantities were obtained by calculating the emissions for an average day within a month by multiplying the weekday value by 5/7 and the weekend value by 2/7 and summing the two values together. Each average daily value for a month was then multiplied by the number of days reported for that month in the MOVES NONROAD input tables to obtain the average monthly emissions. Finally, the average monthly emissions were summed across a year to obtain the annual emission rate. This method was based on instructions from the EPA MOVES team (E.E. Glover, personal communication, September 2, 2015).

For the returned nonroad results generated by MOVES, an additional carbon (C) mass balance check and filtering of records was performed after it was noted that C balance was not preserved in all cases. The fuel C content is reported in the MOVES database for each fuel type. It was assumed the total C in the emissions was made up of >99% from CO₂ and CO. Thus, the total C contained in CO₂ and CO should sum approximately to the fuel C (mass balance constraint). Based on this assumption, the total mass of carbon in the emissions per kg of fuel consumed was calculated for the various horsepower ranges and compared to C in the fuels based using the following equations.

$$C \text{ Mass Balance} = \frac{C_{\text{emissions}} / \text{Fuel Ratio}}{C_{\text{expected}} / \text{Fuel Ratio}} \quad [1]$$

$$C_{\text{emissions}} = \frac{[CO_2] \times \frac{12 \text{ kg C}}{44 \text{ kg CO}_2} + [CO] \times \frac{12 \text{ kg C}}{28 \text{ kg CO}}}{[BSFC]} = \text{kg Fuel} \quad [2]$$

$$C_{\text{expected}} = \text{carbonContent} \left(\frac{\text{kg C}}{\text{MJ of Fuel Energy}} \right) \times \text{energyContent} \left(\frac{\text{MJ of Fuel Energy}}{\text{kg Fuel}} \right) = \frac{\text{kg C}}{\text{kg Fuel}} \quad [3]$$

where, BSFC is the MOVES output for fuel consumption in kg.

The C mass balance ratio was found to deviate >20% from the expected value of one for a number of equipment classes. Due to these discrepancies, only equipment classes that met mass balance criteria were factored into the calculation of emission and activity factors reported here. For diesel, 4-stroke gasoline, and compressed natural gas engines, only equipment classes with C mass balance within 5% of the expected values were used. For 2-stroke gasoline engines, this had to be expanded to values within 10% to capture any equipment, and for LPG equipment it was expanded to values within 15%. A weighted average by hp-hr. was performed for the average emission and activity factors for each equipment class.

3.1.3 Additional Calculations for On-site Equipment and On-road Vehicles

MOVES reports total PM_{2.5} and PM₁₀. Because PM₁₀ emission quantities include particles ≤ 2.5 μm (PM_{2.5}), the quantity of PM₁₀ was included in the PM factors developed to avoid double counting.

For nonroad processes, only nine emissions are reported by MOVES, and these do not include the specific volatile organic compounds (VOCs), some of which are EPA hazardous air pollutants. The category Total Gaseous Hydrocarbons (THC) reported in MOVES was used to calculate the emission factors for specific volatile organic compounds (VOCs) using specific VOC/THC factors (e.g., xylene/THC) from the National Mobile Emissions Model (USEPA, 2015a).

Locomotive emissions factors for PM, THC, and NO_x were derived from (USEPA, 2009). Factors for other emissions including CO₂, SO₂, and HAPs were adapted from the emission factors developed for the largest diesel engine class (>1200 hp) in the nonroad model.

Truck activity factors in ton-miles the cargo are transported/gallon were estimated from national statistics and the MOVES fuel economy values as described below.

The Bureau of Transportation Statistics reported total truck ton-miles and fuel consumption for 2011, but these statistics were not provided specifically for combination trucks (class 8) and single-unit trucks (classes 6-7). Combination truck and single-unit truck ton-mile/gal factors were then estimated as proportional to the gross weights (tons carried plus vehicle weights) and total miles traveled that were reported from an earlier date (2002). The following equations were used to make these calculations:

$$CT_{tmg} = pST_{tmg} \quad [4]$$

$$T_{tmg} = CT_{gtmg} + ST_{gtmg} \quad [5]$$

$$CT_{gtmg} = \frac{CT_{gt} * CT_{vmt}}{CT_{gal}} \quad [6]$$

$$ST_{gtmg} = \frac{ST_{gt} * ST_{vmt}}{ST_{gal}} \quad [7]$$

CT_{tmg} = Combination truck ton-mile/gallon ST_{tmg} = Single unit truck ton-mile/gallon
 p = Combination truck gross ton-mile/gallon/short ton-mile gallon T_{tmg} = Total truck ton-miles/gallon.

CT_{gtmg} = Combination truck gross ton-mile/gallon

ST_{gtmg} = Single unit truck gross ton-mile/gallon

CT_{gt} = Combination truck gross tons

ST_{gt} = Single unit truck gross tons

CT_{vmt} = Combination truck vehicle miles traveled

ST_{vmt} = Single unit truck vehicle miles traveled

CT_{gal} = Combination truck gallons consumed

ST_{gal} = Single unit truck gallons consumed

T_{mg} was provided by the combination of BTS (ton-miles) and FHWA (gallons) (BTS, 2015; FHWA, 2015). Gross weights and vehicle miles traveled for the two trucks types were provided for combination and short trucks by the BTS (BTS, 2015). The same sources provided the tonmile/gallon ratio for freight, but no breakdown of into subtypes was necessary.

3.2 Modeling in the Federal LCI Data Template and openLCA

Data from the above sources were compiled into LCI unit processes using the current EPA version of the Federal LCI unit process template. All chemical emission names, categories and units were harmonized using the Beta 1 version of the LCA Harmonization Tool (W. Ingwersen et al.). The Excel® to OLCA program was used to import the unit processes into an openLCA

1.4.2 database. Models were compiled and managed in the open-source LCA software OpenLCA 1.4.2 (GreenDelta, 2015). An openLCA “product system” was made from each unit process model. The product systems were further imported into their respective openLCA “Projects” from which results were calculated by creating project reports. Report results were copied into the final master dataset spreadsheet file.

3.3 Emission Factor Results for Vehicles and Equipment

3.3.1 Dataset File

The full dataset is available upon request in the file “Fuel, Equipment and Transport Emission and Activity Factors for SEFA.xlsx.” The resulting factors are summarized in Section 1.1.

3.3.2 Supporting Data

The following files are available as supporting data to the dataset and are available upon request. These include:

File name	Description
SEFAfuelequiptransportfactors.zolca	openLCA database
SEFAfuelequiptransportfactors_templates.zip	The Federal LCI unit process templates
SEFAfuelequiptransportfactors_MOVESrunspecs.zip	MOVES 2014 run file
SEFAfuelequiptransportfactors_MOVESSqlresults.zip	SQL queries for MOVES output databases
SEFAfuelequiptransportfactors_supportingExcel.zip	Results of SQL queries and emissions data processing for Fed LCI template incorporation

3.4 SEFA Vehicle and Equipment Emission Factory Summary

Table 20. Summary of SEFA Emission Factors for Vehicle and Equipment Operations

			Emission Factors						Activity Factors	
			Energy	GHG	NOx	SOx	PM	HAPs	Factor	Value
			Used	Emitted	Emitted	Emitted	Emitted	Emitted		
Item or Activity	Fuel	Unit	MMBtu	lbs CO2e	lbs	lbs	lbs	lbs		
Fuels upstream¹, except where noted										
Fuel production and distribution to retail	Diesel	gal	0.156	3.02	0.0051	0.0062	0.0017	0.0011	NA	
Fuel production and distribution to retail	Gasoline	gal	0.157	2.80	0.0046	0.0050	0.0015	0.0010	NA	
Fuel production and distribution to retail	Liquefied Petroleum Gas	gal	0.088	1.47	0.0016	0.0024	0.0007	0.0003	NA	
Fuel production and distribution to retail	Compressed Natural Gas ²	ccf	19.983	343.92	0.4732	2.1651	0.1846	0.2895	NA	
On-site equipment use³										
equipment operation, < 25 hp	Diesel	gal	NA	22.20	0.170	0.00015	0.016	0.00004	hp-hr./gal	16.4
equipment operation, > 25 hp and < 75 hp	Diesel	gal	NA	22.22	0.143	0.00014	0.013	0.00004	hp-hr./gal	16.3
equipment operation, > 75 hp and < 750 hp	Diesel	gal	NA	22.24	0.101	0.00013	0.009	0.00004	hp-hr./gal	18.2
equipment operation, > 750 hp and < 1200 hp	Diesel	gal	NA	22.24	0.157	0.00013	0.006	0.00004	hp-hr./gal	18.8
equipment operation, > 1200 hp	Diesel	gal	NA	22.24	0.141	0.00013	0.006	0.00004	hp-hr./gal	18.8

			Emission Factors						Activity Factors	
			Energy	GHG	NOx	SOx	PM	HAPs	Factor	Value
			Used	Emitted	Emitted	Emitted	Emitted	Emitted		
Item or Activity	Fuel	Unit	MMBtu	lbs CO2e	lbs	lbs	lbs	lbs		
equipment operation, < 25 hp	Gasoline	gal	NA	17.48	0.037	0.00025	0.165	0.00008	hp-hr./gal	0.0002
equipment operation, > 25 hp and < 75 hp	Gasoline	gal	NA	19.93	0.032	0.00029	0.002	0.00009	hp-hr./gal	12.9
			Emission Factors						Activity Factors	
			Energy	GHG	NOx	SOx	PM	HAPs	Factor	Value
			Used	Emitted	Emitted	Emitted	Emitted	Emitted		
Item or Activity	Fuel	Unit	MMBtu	lbs CO2e	lbs	lbs	lbs	lbs		
equipment operation, > 75 hp and < 750 hp	Gasoline	gal	NA	19.93	0.032	0.00029	0.002	0.00009	hp-hr./gal	12.9
equipment operation, > 25 hp and < 75 hp	Liquefied Petroleum Gas	gal	NA	12.69	0.021	0.00013	0.001	0	hp-hr./gal	10.4
equipment operation, > 75 hp and < 750 hp	Liquefied Petroleum Gas	gal	NA	12.69	0.021	0.00013	0.001	0	hp-hr./gal	10.4
equipment operation, > 25 hp and < 75 hp	Compressed Natural Gas	ccf	NA	1953.25	16.153	0.02299	0.281	0	hp-hr./ccf	2031.0
equipment operation, > 75 hp and < 750 hp	Compressed Natural Gas	ccf	NA	1962.42	15.912	0.02310	0.274	0	hp-hr./ccf	2031.0

Personal Transport³										
passenger car, gasoline	Gasoline	gal	NA	19.77	0.027	0.00036	0.003	0.00670	miles/gal	25.0
passenger car, diesel	Diesel	gal	NA	22.57	0.015	0.00020	0.003	0.00252	miles/gal	28.4
passenger car, fleet average	Gasoline/diesel mix	gal	NA	19.79	0.027	0.00036	0.003	0.00668	miles/gal	25.0
passenger truck, gasoline	Gasoline	gal	NA	19.79	0.035	0.00036	0.003	0.00661	miles/gal	18.9
passenger truck, diesel	Diesel	gal	NA	22.54	0.055	0.00020	0.006	0.00244	miles/gal	15.1
passenger truck, fleet average	gasoline/diesel mix	gal	NA	19.85	0.036	0.00036	0.003	0.00655	miles/gal	18.8
work truck, LHD and MHD	Diesel	gal	NA	22.55	0.062	0.00020	0.008	0.00277	miles/gal	15.7
Transport of Goods and Services^{3,except where}										
			Emission Factors						Activity Factors	
			Energy Used	GHG Emitted	NOx Emitted	SOx Emitted	PM Emitted	HAPs Emitted	Factor	Value
Item or Activity	Fuel	Unit	MMBtu	lbs CO ₂ e	lbs	lbs	lbs	lbs		
<i>noted</i>										
combination truck	Diesel	gal	NA	22.53	0.122	0.00020	0.011	0.00205	tonmile/gal	65.2 _{4,5}
single-unit truck	Diesel	gal	NA	22.52	0.088	0.00020	0.012	0.00196	tonmile/gal	31.0 _{4,5}

Personal Transport³										
freight train	Diesel	gal	NA	25.26	0.307 ⁶	0.0063 4	0.009 ⁶	0.00444 ⁶	tonmile/gal	465.1 ⁴ , ⁵

Notes. LHD = Light-heavy duty; MHD = Medium-heavy duty; NA = not applicable.

The number of decimal places presented is for presentation purposes but the precise number of significant figures could not be determined due to the use of numerous data sources where these were not reported.

Sources: (1) Sengupta et al. 2014 (2) NREL 2008 (3) USEPA 2014c (4) BTS 2015 (5) FHWA 2015 (6) EPA 2009.

4.0 Analytical Services

4.1 Methodology

The remediation of a contaminated site can require extensive amounts of energy, materials, time, and money. A key activity of site remediation is site monitoring involving the use of analytical chemistry services to identify an analyte (i.e., chemical species) and quantify its concentration in soil and groundwater samples. This information is crucial to the success of a site's remediation because it determines if concentrations are reduced to levels that are considered safe for human and ecological exposure. When considering green remediation, the contribution of analytical services to a site's footprint is often overlooked. There are currently no existing databases or literature that quantify life cycle inventories for analytical chemistry services. Therefore, the following chapter addresses this knowledge gap by developing life cycle inventories for various analytical services and establishing EmFs to include for consideration in EPA's SEFA. This research was requested by EPA's Region 9 (Pacific Southwest) Office and NRMRL's Engineering Technical Support Center, on behalf of EPA's Office of Superfund Remediation and Technology Innovation (OSRTI). The results will be used by OSTRI to update SEFA.

This chapter focuses on creating EmFs for analytical testing activities promulgated under the Clean Water Act (CWA) section 304(h). The analytical methods outlined in section 304(h) (see Table A1.1) are used to measure chemical and biological pollutants in media such as wastewater, ambient water, sediment, and biosolids (sewage sludge). The methods are used in a variety of labs and matrices (e.g., solid, water) and several methods may be used to quantify a single analyte, where each analyte's detectable concentration will determine its associated method. The specific analytical techniques identified for this study included gas chromatography, liquid chromatography, gravimetric extraction, spectroscopy (i.e., atomic adsorption, atomic fluorescence, colorimetry, conductance, distillation, electrochemical, inductively coupled plasma, pH, and turbidity), thermal chromatography, and ion chromatography. The 304(h) analytical methods were an ideal focus for this study, particularly because they represent a broad range of analytical methods commonly used at remediation sites.

Life cycle inventories for analytical methods using these techniques were created by first developing a general life cycle model of an analytical service that can combine both secondary data and expert judgment about the execution of the various procedures within a method to model specific method inventories. The general model was customized to generate life cycle inventories for 85 methods from the CWA section 304(h). The functional unit varied by method, where the functional unit was a given analytical method based on three scenarios: 100 analyzed field samples, 5 analyzed quality control samples (per 20 analyzed field samples), and 5 analyzed calibration curve samples (per 20 analyzed field samples); 1 analyzed field sample with no quality control or calibration curve samples; and, 3.5 analyzed quality control samples and 5 analyzed calibration

curve samples with no analyzed field samples. The first scenario's results are stand-alone, while the second and third scenarios are meant to be used together to achieve a user's desired results.

4.1.1 Sample Collection, Sample Preparation, Analysis, and Disposal

The general model decomposes the analytical method into four phases: sample collection, sample preparation, analysis, and disposal. The sample collection phase includes all activities related to receiving an analyte in its associated media at the laboratory from a given field location. However, activities related to actual field sampling (such as sampling personnel travel to the site and field sample containers) were not included in the analysis because they are considered separately in SEFA. The sample preparation phase includes all products and processes related to treating a sample prior to its analysis. The sample preparation step is crucial because methods are often not responsive to an analyte in its *in-situ* form and the results are distorted by interfering analytes. Sample preparation may involve reaction with any number of chemical species, dissolution, pulverizing, masking, dilution, filtering, sub-sampling or many other techniques. The analysis phase includes all products and processes used to quantify the analyte of interest. The analysis phase primarily uses non-consumables, which includes but is not limited to the following equipment: thermionic bead detector, alkali flame detector, electron capture detector, flame ionization detector, flame photometric detector, photoionization detector, spectrophotometer, electrochemical detector, colorimeter, and chromatograph. The disposal phase includes disposal of products, chemicals, and those processes used to dispose of the products and chemicals utilized in the two preceding phases (i.e., sample preparation, analysis).

4.1.2 Inventory Modeling

The cradle-to-grave life cycle processes were derived from either processes found in the US EPA life cycle database or from ecoinvent v2.2 (USEPA, 2016; B. Weidema & Hirschier, 2012). Electricity flows and processes were provided by the US EPA life cycle database. All other flows and processes were provided by the ecoinvent database. Aside from geographic inconsistencies between the modeled data and the ecoinvent database (where the ecoinvent database is comprised of primarily European data), the utilized life cycle processes were suitable as inventory based on the modeled data.

To better track material and energy use, inventory items were classified based on both the nature of their use and their associated methodological component. Use-based categories included chemicals, consumables, and non-consumables. Four categories were designated for methodological components, including field samples, quality control samples, calibration curve samples, and general purpose (noting that general purpose inventory was assumed to be created once for the entirety of the analysis, regardless of the number of field samples, quality control samples, or calibration samples analyzed). The use-based categories (i.e., chemicals, consumables, non-consumables) and the methodological component(s) for which they were utilized were originally modeled directly from each method's associated procedure.

4.1.3 Chemicals, Consumables, and Non-Consumables

4.1.3.1 Chemicals

Chemical use can occur during any phase of an analytical chemistry service. For example, chemicals can be used in the form of solvents (e.g., acetone, methyl acetate, ethyl acetate) during the disposal phase, or for making reagents/standards during the sample preparation phase. In total, the model draws upon more than 200 chemicals (see Table A2.1). Of these, 25 chemicals had existing cradle-to-gate life cycle inventory datasets available from databases (see Table 21) that could be used to account for their upstream production in the analytical services model. Chemicals that were described as volumes in a given method's literature were converted to masses using each chemical's respective density. The online database PubChem provided chemical density values (National Center for Biotechnology, 2004). Published and maintained by the National Center for Biotechnology, PubChem is an online database that provides biological activities of small molecules.

Table 21. Chemicals with Available Life Cycle Inventories

Chemical	Database
2,4-D	ecoinvent v2.2
Acetone	ecoinvent v2.2
Acetonitrile	ecoinvent v2.2
Ammonium Chloride	ecoinvent v2.2
Ammonium Nitrate	ecoinvent v2.2
Ammonium Sulfate	ecoinvent v2.2
Benzene	ecoinvent v2.2
Carbitol	ecoinvent v2.2
Deionized Water	ecoinvent v2.2
Dicamba	ecoinvent v2.2
Ethyl Acetate	ecoinvent v2.2
Ethylenediaminetetraacetic Acid	ecoinvent v2.2
Helium Gas	ecoinvent v2.2
Hexane	ecoinvent v2.2
Hydrochloric Acid	ecoinvent v2.2
Methanol	ecoinvent v2.2
Methyl Tert-Butyl Ether	ecoinvent v2.2
Nitric Acid	ecoinvent v2.2
Phosphoric Acid	ecoinvent v2.2
Potassium Chloride	ecoinvent v2.2
Potassium Hydroxide	ecoinvent v2.2
Sodium Carbonate	ecoinvent v2.2
Sodium Chloride	ecoinvent v2.2
Sodium Hydroxide	ecoinvent v2.2

Chemicals not currently included in existing life cycle inventory databases were classified as either organic or inorganic and modeled as an unweighted average of the top 20 organic or inorganic chemicals by use in the ecoinvent v2.2 database. The top-twenty lists of organic and inorganic chemicals are shown in Table 22. For the current inventory development, chemical disposal was excluded based on a lack of inventory data. While the disposal of chemicals could have been lumped into non-hazardous municipal solid or liquid waste, such an assumption would not have been suitable due to the increased environmental and human health impacts associated with disposing chemicals as opposed to non-chemical waste.

Table 22. Chemicals used to calculate average life cycle impacts for unlisted organic and inorganic chemicals

Organics		Inorganics	
Chemical	Database	Chemical	Database
Acetic Acid	ecoinvent v2.2	Aluminum Sulfate	ecoinvent v2.2
Acetone	ecoinvent v2.2	Ammonia	ecoinvent v2.2
Benzene	ecoinvent v2.2	Ammonium Nitrate	ecoinvent v2.2
Butadiene	ecoinvent v2.2	Ammonium Sulfate	ecoinvent v2.2
Ethyl Benzene	ecoinvent v2.2	Calcium Chloride	ecoinvent v2.2
Ethylene	ecoinvent v2.2	Chlorine	ecoinvent v2.2
Ethylene Dichloride	ecoinvent v2.2	Hydrochloric Acid	ecoinvent v2.2
Ethylene Glycol	ecoinvent v2.2	Hydrogen Fluoride	ecoinvent v2.2
Ethylene Oxide	ecoinvent v2.2	Nitric Acid	ecoinvent v2.2
Formaldehyde	ecoinvent v2.2	Nitrogen	ecoinvent v2.2
Methanol	ecoinvent v2.2	Oxygen	ecoinvent v2.2
Methyl Tert-Butyl Ether	ecoinvent v2.2	Phosphoric Acid	ecoinvent v2.2
Phenol	ecoinvent v2.2	Quicklime	ecoinvent v2.2
Propylene	ecoinvent v2.2	Soda Powder	ecoinvent v2.2
Styrene	ecoinvent v2.2	Sodium Chlorate	ecoinvent v2.2
Toluene	ecoinvent v2.2	Sodium Hydroxide	ecoinvent v2.2
Urea	ecoinvent v2.2	Sodium Silicate	ecoinvent v2.2
Vinyl Acetate	ecoinvent v2.2	Sodium Sulfate	ecoinvent v2.2
Vinyl Chloride	ecoinvent v2.2	Sulfuric Acid	ecoinvent v2.2
Xylene	ecoinvent v2.2	Titanium Dioxide	ecoinvent v2.2

4.1.3.2 Consumables

The consumables category encompassed all disposable products, where each consumable is used once and then disposed. Consumables are subject to regulations and/or laboratory protocols stipulating their utilization not exceed one instance. Table A3.1 lists the processes utilized to construct the cradle-to-grave life cycle inventory associated with the evaluated consumables. This list contains the upstream processes used to manufacture elementary and/or technosphere

flows into usable products, processes used to transport the manufactured consumables from the manufacturer to the user and from the user to the disposal site, and processes used to model the disposal of consumables. Materials comprising consumables were determined by a consumable's corresponding manufacturer literature (e.g., user manuals, product specifications). These materials were cross-referenced with the most suitable flows in either ecoinvent or the US EPA life cycle database. Material specifications and masses for consumables were obtained from a range of primary measurements and secondary sources, which are shown in Table A3.2. Inventory values were interpolated for consumables that did not report explicit weights. The values associated with these consumables were interpolated from consumables that were identical in function and material but ranged in size (e.g., 100mL polypropylene beaker vs. 500 mL polypropylene beaker corresponded with a 500% increase). The model did not include packaging materials for any given consumable.

Transportation flows used to model procurement and disposal were based on values provided by the 2012 Commodity Flow Survey (USDOT & USDOC, 2015). Consumables were assumed to correspond with the Standard Classification of Transported Goods (SCTG) code: 28, or 'Precision instruments and apparatus'. Its 2012 truck, rail, water, and air transported ton values were normalized to the average shipment length of 1,565 kilometers. Or, the distance per truck shipment for consumables was 1,472 kilometers, and the distance per air shipment for consumables was 123 kilometers. These values are shown in Table 23. Similarly, chemicals were assumed to correspond with the North American Industry Classification System (NAICS) code: 325, or 'Chemical manufacturing'. Its 2012 truck, rail, water, and air transported ton values were normalized to the average shipment length of 1,814 kilometers for multiple modes. Or, the distance per truck shipment for chemicals was 1,058 kilometers, the distance per rail shipment for chemicals was 585 kilometers, the distance per water shipment for chemicals was 169 kilometers, and the distance per air shipment for chemicals was approximately 2 kilometers. These values are shown in Table 24.

Table 23. Transport values for: 38 - Precision Instruments and Apparatus (SCTG code)

Average kilometers per shipment		1594.9	
Mode of transportation	2012 tons (thousands)	Percent of total	Average kilometers per shipment
Truck	4,654	92.3%	1,472
Rail	0	0%	0
Water	0	0%	0
Air	389	7.7%	123

Table 24. Transport values for: 325 - Chemical Manufacturing (NAICS code)

Average kilometers per shipment		1813.7	
Mode of transportation	2012 tons (thousands)	Percent of total	Average kilometers per shipment
Truck	312,547	58.3%	1,058
Rail	172,892	32.3%	585
Water	49,854	9.3%	168
Air	567	0.1%	2

Several flows were used to model the forming and shaping of materials into consumables. Steel and aluminum were represented by life cycle processes related to the shaping and forming of steel and aluminum. Several plastics were grouped together and modeled as plastic injection molding. These plastics included: polyvinylchloride, low-density polyethylene, polypropylene, polycarbonate, and polyurethane. Of the three inventory categories (i.e., chemicals, consumables, and non-consumables), consumables are the only category to include disposal processes. Disposal processes and/or flows were assumed to be inputs into the modeled system. Disposal processes were entirely provided by the ecoinvent v2.2 database and are further detailed in Table A3.1.

4.1.3.3 Non-consumables

Non-consumables encompass all products and/or devices that were used more than once before requiring disposal. There were two primary examples of non-consumables: those that required cleaning, and those that required no cleaning but were associated with some level of electricity consumption. Electricity consumption values for corresponding non-consumables were based on a range of secondary data, which are further detailed in Table A4.1. The model utilized an average US electricity grid based on industrial (as opposed to residential) use. A common example of non-consumables requiring cleaning was glassware, which was primarily associated with deionized water and cleaning agent life cycle flows. The primary inventories associated with non-consumables were related to cleaning requirements. Due to the higher level of uncertainty and increased number of necessary assumptions associated with allocating flows to reusable products, the upstream manufacturing and transportation associated with nonconsumables were excluded from analysis. Consumables and chemicals were assumed to not require any form of cleaning. Where applicable, non-consumable equipment was assumed to be cleaned with Luminox®. Luminox® is a phosphate-free detergent with the capability of removing oils and organic contamination.

Luminox® is recommended for cleaning laboratory equipment by the Field Equipment Cleaning and Decontamination Operating Procedure released by Region 4 of the US EPA Science and Ecosystem Support Division (USEPA, 2015b). The Luminox® technical bulletin recommends 30-50 mL of Luminox® per liter of deionized water (Alconox, 2006). The analysis assumes 50 mL of

Luminox® per liter of deionized water. The volume of deionized water used in conjunction with Luminox® was assumed to be equivalent to the volume of the equipment requiring cleaning. For example, a 1 liter flask would require 1 L of deionized water and 50 mL of Luminox®. The Luminox® material safety data sheet (MSDS) lists the ingredients found in Luminox®; those ingredients include: water (40-60% by weight), dipropylene glycol monomethyl ether (20-30 by weight), propylene glycol n-butyl ether (1-10% by weight), monoisopropanol amine (1-5% by weight), and glycolic acid (1-5% by weight) (Alconox, 2011). Due to restraints associated with chemical availability in life cycle databases, only deionized water and dipropylene glycol monomethyl ether were included in the analysis. The assumed ratio of water to dipropylene glycol monomethyl ether was 2:1 for Luminox®. Following cleaning with the assumed Luminox® solution, the equipment was then assumed to be rinsed with an equal volume of deionized water (e.g., one liter).

4.1.4 Field Samples, Quality Control Samples, Calibration Curve Samples, and General Purpose

Equation 1 shows the calculations used to model the inventory requirements for field samples. Field samples are collected from the site of interest and can take the form of several media, including air, liquid, and solid. Equation 1 includes the four variables related to chemical, consumable, and non-consumable inventory requirements for one sample. The multiplier for these four variables is the of number field samples analyzed, which equates to the field sample inventory requirements for any given number of analyzed field samples.

$$F = x \sum (Ch_i + Co_i + Nc_i) \quad [1]$$

F = Field sample inventory requirements x

= Number of field samples analyzed

Ch = Chemical inventory requirements for one sample

Co = Consumable inventory requirements for one sample Nc

= Non-consumable inventory requirements for one sample i =

Denotes a flow

Equation 2 shows the calculations used to model the inventory requirements for quality control samples. Quality control samples are used to check laboratory performance with externally prepared test materials. They are solutions of method analytes of known concentrations that are obtained from a source external to the laboratory and different from the source of calibration samples. Equation 3 shows the calculations used to model inventory requirements for calibration curve samples. Calibration curve samples are used to calibrate an instrument's response with respect to analyte concentration. There are solutions prepared from the dilution of the primary standard solution or from stock standard solutions. While the establishment of a calibration curve is typically considered an element of quality control, all inventory requirements associated with

establishing a calibration curve are assumed to be mutually exclusive with quality control inventory requirements. Calibration curve inventory requirements were kept mutually exclusive from quality control inventory requirements to eliminate the possibility of double-counting inventory. Double-counting would occur if the calibration curve and quality control inventory requirements were not kept separate, due to the calibration curve being reestablished with each batch of quality control samples *and* being reestablished with each analysis batch.

The quality control and calibration curve inventory requirements increase linearly when the number of analyzed field samples exceeds the method's maximum number of field samples for an analysis batch; where an analysis batch is a sequence of samples that includes all required quality control and calibration curve samples. For example, a hypothetical method may allow 20 field samples per analysis batch and require y quality control samples and z calibration curve samples per analysis batch. The hypothetical method would then require y quality control samples and z calibration curve samples if analyzing 1 to 20 field samples, $2y$ quality control samples and $2z$ calibration curve samples if analyzing 21 to 40 field samples, $3y$ quality control samples and $3z$ calibration curve samples if analyzing 41 to 60 field samples, etc. Similar to Equation 1, Equation 2 and Equation 3 include the four variables related to chemical, consumable, and non-consumable inventory requirements for one sample. Unlike Equation 1, Equation 2 and Equation 3 include the modulo operator (mod). The modulo operator finds the remainder after division of one number by another. For the purposes of Equation 2 and Equation 3, the modulo operator allows for the quality control and field sample inventory requirements to increase linearly given the number of field samples analyzed and the maximum number of field samples for each analysis batch. The primary differentiator between Equation 2 and Equation 3 are the variables y and z , or the number of quality control samples required for each analysis batch and the number of calibration curve samples required for an analysis batch, respectively.

$$= \left\{ y \times \left[1 + \frac{x}{x_{max}} \right] \right\} \sum (Ch_i + Co_i + Nc_i) - (x \bmod x_{max}) \quad [2]$$

Q = Quality control inventory requirements

x_{max} = Maximum number of field samples for an analysis batch

y = Number of quality control samples required for an analysis batch

$$= \left\{ z \times \left[1 + \frac{x}{x_{max}} \right] \right\} \sum (Ch_i + Co_i + Nc_i) - (x \bmod x_{max}) \quad [3]$$

C = Calibration curve inventory requirements

z = Number of calibration curve samples required for an analysis batch

General purpose inventory was assumed to be created once for the entirety of the analysis, regardless of the number of field samples, quality control samples, or calibration samples analyzed. Otherwise, a general purpose solution was assumed to be made once and the amount of solution initially mixed was assumed to be a sufficient amount for the duration of the method. The most common example of general purpose inventory was the creation of solutions, reagents, and/or standards.

4.1.5 Assumptions

In addition to the aforementioned assumptions, the model includes several additional assumptions that govern its applicability and use. The assumptions are as follows:

- A method is performed as defined by the method's corresponding Clean Water Act section 304(h) report.
- The number of people performing any given phase did not affect variables (i.e., time, inventory) for those phases.
- Quality control and calibration curve samples fall within intended guidelines, protocols, and/or ranges, or, utilized products and equipment operate under recommended conditions and within calibration limits (i.e., best-case scenario).
- Utilized equipment was assumed to be dedicated to a given method, and/or the equipment was not used for any purposes beyond a given method.
- A number of methods did not specify an analysis time or a value quantifying how many samples were analyzed on a temporal basis. These methods were assumed to have an analysis time of 30 minutes.
- An analysis batch does not exceed 20 samples.
- Methods that did not specify a number of quality control points were assumed to have five quality control points.
- Methods that did not specify a number of calibration curve points were assumed to have five calibration curve points.
- Overhead and/or indirect processes related to an analytical method were not included. These processes included (but were not necessarily limited to): building utilities (e.g., water, heating, cooling) and building personnel.

4.2 Inventory Analysis and EmF Calculations

Figure 24 shows the workflow of life cycle inventory calculations, with consumables and chemicals modeled using manufacturing, transport, and disposal processes. Manufacturing, transport, and disposal processes utilized primary and secondary data (see Table A3.2). Nonconsumables were built on secondary data, where the secondary data represented electricity consumption specifications for each respective non-consumable. Each analytical service was

inventoried for consumables, chemicals, and non-consumables. These inventory data were entered into a Microsoft Excel®-based model. Bridge processes were utilized in order to link each consumable, chemical, and non-consumable with existing life cycle inventory databases. This enables the models to be connected to any desired background database. The Microsoft Excel®-based model with bridge processes was then exported to the FED LCI Unit Process Template using a series of macros. The FED LCI Unit Process was then exported to the opensource life cycle assessment software OpenLCA 1.4.2 using a series of scripts. The models were compiled and managed in OpenLCA. OpenLCA “Processes” were created for each of the 85 analytical methods, where each “Process” provided emission factors for each method.

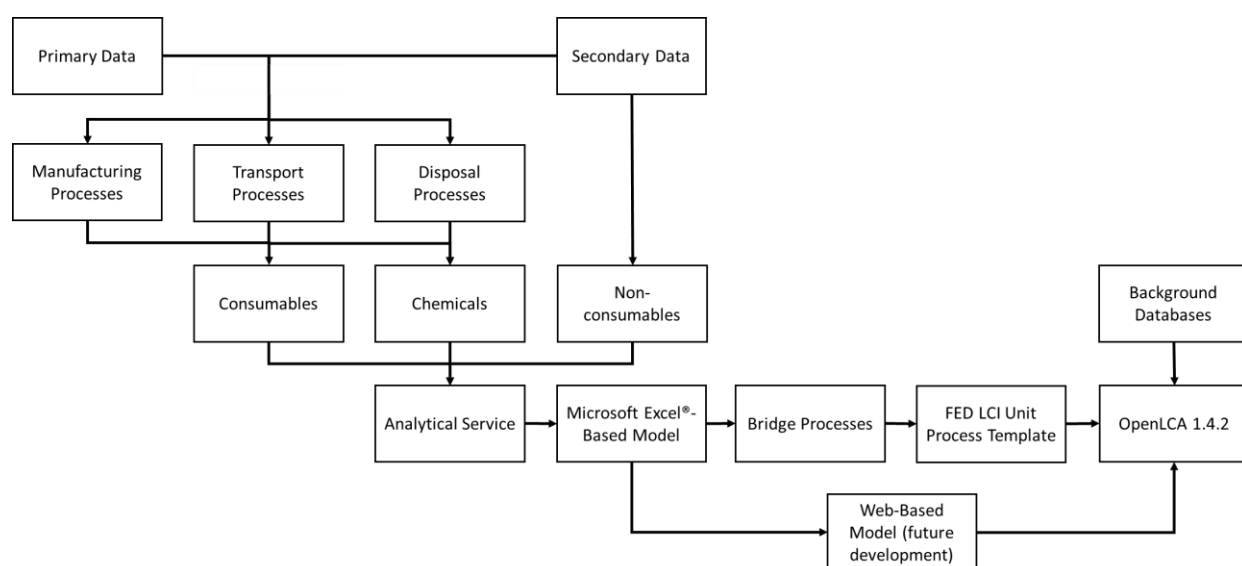


Figure 24. Workflow of life cycle inventory calculations

OpenLCA used several background databases (i.e., USLCI, ecoinvent v2.2, US EPA life cycle database) to build emission factors for each analytical service, which were analyzed based on eight footprint categories. The footprint categories included: NO_x (kg NO_x), SO_x (kg SO_x), Global Warming: GWP₁₀₀ (Global Warming Potential, kg CO₂ eq), Water Use (m³ H₂O), PM₁₀ (kg PM), HAPs (kg HAPs), Fossil Depletion: FDP (Fossil Depletion Potential, kg oil eq), and Energy Demand: CED (Cumulative Energy Demand, MJ). Footprinting is analogous to impact assessment in LCA, but differs because the characterization factors (CFs) used to translate the elementary flow values to footprint category values typically have a value of one. As shown in Equation 4, this leads to a simple summation of all like elementary flows into an emission factor for each desired footprint category.

$$EmF_k = \sum_{i=1}^m \sum_{j=1}^n F_{i,j,k} \times CF_{j,k} \quad [4]$$

i = Unit process

j = Individual flow that contributes to an emission factor k = Impact

category m = Maximum number of unit process represented in the LCI n =

Maximum number of flows included in the emission factor

The exceptions to this approach are the categories of CED and GWP, where inventory flows are converted to energy (MJ) and carbon dioxide equivalents (CO₂ eq), respectively. In these cases, the characterization factors have values other than one, as defined in each methodology's documentation. Although CED is still a footprinting category because it makes no evaluation of the impact of energy demand, GWP does consider the potency of substances for inducing global warming when converting to carbon dioxide equivalents and is therefore more like an impact indicator.

4.3 Method 314.0 Case Study

A case study is presented to illustrate the model's operations and capabilities. The case study utilizes the procedure (i.e., field sample analysis, quality control, and calibration curve) and equipment described in Method 314.0. Using ion chromatography, Method 314.0 covers the determination of perchlorate in surface water, reagent water, ground water, and drinking water. A 1.0 mL sample volume is introduced into an ion chromatograph, where the perchlorate is separated and measured using a system comprised of an ion chromatographic pump, sample injection valve, guard column, analytical column, suppressor device, and conductivity detector (Hautman, Munch, Eaton, & Haghani, 1999).

4.3.1 Assumptions

The Method 314.0 case study includes several additional assumptions that govern its applicability and use (Hautman et al., 1999). The assumptions apply solely to Method 314.0. The assumptions are as follows:

- Each individual sample requires 15 minutes for analysis.
- The ion chromatograph and computer with data acquisition system are operated for the duration of each sample's respective analysis, which includes all field samples, quality control samples, and calibration curve samples.
- The analytical balance and conductivity meter are operated for 30 minutes.
- The model does not include helium purging for 10 minutes (described in Section 7.2.2).

- The model does not include the matrix pretreatment cartridges in the barium, silver, and hydrogen form (described in 6.12 to 6.14).
- The eluent is 2L of 50mM NaOH.

4.3.2 Inventory

Table 25 shows the flows that characterize Method 314.0. Each flow's category, amount (with associated units), method category (i.e., field sample, quality control, calibration curve), method subcategory (i.e., chemical, consumable, non-consumable), and phase (i.e., sample preparation, analysis, disposal) are shown.

Table 25. Flows used to characterize Method 314.0.

Flow	Amount	Unit	Method Category	Method Subcategory	Phase
Syringe with luer lock; 20mL; polypropylene; at user	1.00E+02	Item(s)	Field sample	Consumable	Sample preparation
Particulate filter; polycarbonate; at user	1.00E+02	Item(s)	Field sample	Consumable	Sample preparation
Micro beaker; 100mL; polypropylene; at user	1.00E+02	Item(s)	Field sample	Consumable	Sample preparation
Syringe with luer lock; 20mL; polypropylene; at user	6.00E+01	Item(s)	Calibration curve	Consumable	Sample preparation
Conductivity meter; at user; one hour of use	5.00E+01	Item(s)	Field sample	Nonconsumable	Analysis
Vial with cap; 10 mL; polypropylene; at user	3.00E+01	Item(s)	Quality control	Consumable	Sample preparation
Vial with cap; 10 mL; polypropylene; at user	3.00E+01	Item(s)	Calibration curve	Consumable	Sample preparation
Syringe with luer lock; 20mL; polypropylene; at user	3.00E+01	Item(s)	Quality control	Consumable	Sample preparation
Pipette tip; 5 mL; low-density polyethylene; at user	3.00E+01	Item(s)	Quality control	Consumable	Sample preparation
Particulate filter; polycarbonate; at user	3.00E+01	Item(s)	Calibration curve	Consumable	Sample preparation
Micro beaker; 100mL; polypropylene; at user	3.00E+01	Item(s)	Calibration curve	Consumable	Sample preparation

Flow	Amount	Unit	Method Category	Method Subcategory	Phase
Ion chromatograph; Dionex ICS5000; at user; one hour of use	2.50E+01	Item(s)	Field sample	Nonconsumable	Analysis

CUTOFF: Disposal; polypropylene; 0% water; to sanitary landfill	1.92E+01	kg	General purpose	Disposal	Disposal
Ion chromatograph; Dionex ICS5000; at user; one hour of use	7.50E+00	Item(s)	Quality control	Nonconsumable	Analysis
Ion chromatograph; Dionex ICS5000; at user; one hour of use	7.50E+00	Item(s)	Calibration curve	Nonconsumable	Analysis
Weigh boat; large; polystyrene; at user	6.00E+00	Item(s)	General purpose	Consumable	Sample preparation
CUTOFF: Deionized water; laboratory grade	5.21E+00	kg	General purpose	Chemical	Sample preparation
Weigh boat; medium; polystyrene; at user	5.00E+00	Item(s)	N/A	Consumable	N/A
Pipette tip; 5 mL; low-density polyethylene; at user	4.00E+00	Item(s)	General purpose	Consumable	Sample preparation
Pipette tip; 5 mL; low-density polyethylene; at user	4.00E+00	Item(s)	N/A	Consumable	0
Micro beaker; 100mL; polypropylene; at user	2.00E+00	Item(s)	General purpose	Consumable	Sample preparation
CUTOFF: Sodium sulfite	1.00E+00	kg	General purpose	Consumable	Sample preparation
Analytical balance; 0.1 mg capability; at user; one hour of use	5.00E-01	Item(s)	General purpose	Nonconsumable	Sample preparation
Analytical balance; 0.1 mg capability; at user; one hour of use	4.17E-01	Item(s)	N/A	Nonconsumable	N/A
CUTOFF: Disposal; plastics; mixture; 0% water; to sanitary landfill	1.18E-01	kg	General purpose	Disposal	Disposal
CUTOFF: Deionized water; laboratory grade	1.05E-01	kg	Calibration curve	Chemical	Sample preparation
CUTOFF: Disposal; polyethylene; 0% water; to sanitary landfill	6.84E-02	kg	General purpose	Disposal	Disposal
CUTOFF: Disposal; polystyrene; 0% water; to sanitary landfill	3.90E-02	kg	General purpose	Disposal	Disposal
CUTOFF: Deionized water; laboratory grade	2.78E-02	kg	N/A	Chemical	Sample preparation
CUTOFF: Dipropylene glycol monomethyl ether	1.33E-02	kg	N/A	Chemical	Sample preparation
CUTOFF: Truck transport; freight	1.16E-02	tkm	General purpose	Chemical	N/A
CUTOFF: Sodium hydroxide	8.00E-03	kg	General purpose	Chemical	Sample preparation
CUTOFF: Rail transport; freight	6.42E-03	tkm	General purpose	Chemical	N/A
CUTOFF: Water transport; freight	1.85E-03	tkm	General purpose	Chemical	N/A
CUTOFF: Sodium carbonate	1.10E-03	kg	General purpose	Chemical	Sample preparation

CUTOFF: Disposal; polypropylene; 0% water; to sanitary landfill	1.92E+01	kg	General purpose	Disposal	Disposal
Flow	Amount	Unit	Method Category	Method Subcategory	Phase
CUTOFF: Sodium chloride	1.00E-03	kg	General purpose	Chemical	Sample preparation
CUTOFF: Potassium chloride	7.45E-04	kg	General purpose	Chemical	Sample preparation
CUTOFF: Sodium perchlorate	1.23E-04	kg	General purpose	Chemical	Sample preparation
CUTOFF: Air transport; freight	2.10E-05	tkm	General purpose	Chemical	N/A

*The term “CUTOFF” signifies flows that are bridged from non-EPA life cycle inventory databases (e.g., ecoinvent v2.2). The “CUTOFF” term is used to standardize naming conventions for different life cycle inventory databases.

4.3.3 Emission Factor Results

Figure 25 illustrates the flows that are most significant with respect to the eight analyzed emission factors. The use of polypropylene in consumables was the most significant driver for energy demand, fossil depletion, global warming, and water use. Method 314.0 calls for a number of consumables, where the analysis assumed the utilized consumables were composed of polypropylene. In many instances Method 314.0's procedure did not stipulate the utilized consumables be comprised of polypropylene. Therefore, there would be a shift in environmental impacts when there is a shift in material(s) comprising the consumables utilized in Method 314.0.

Electricity consumption, particularly the use of coal as an energy source, was the most significant driver for emission factors associated with air quality (i.e., HAPs, NO_x, PM₁₀, SO_x). The use of non-consumables were the primary flows constituting electricity consumption. These non-consumables included the conductivity meter, ion chromatograph, and analytical balance. The electricity grid mix used for this model was based on the average for US electricity production. Because electricity consumption was significant with respect to air quality emission factors, a shift in the electricity grid mix would shift air quality environmental impacts accordingly. For example, coal is typically associated with higher air quality impacts when compared to renewable energy sources (e.g., solar and wind power) (Bates, Watkiss, & Thorpe, 1996). Therefore, a shift towards renewable energy sources would cause a decrease in air quality impacts.

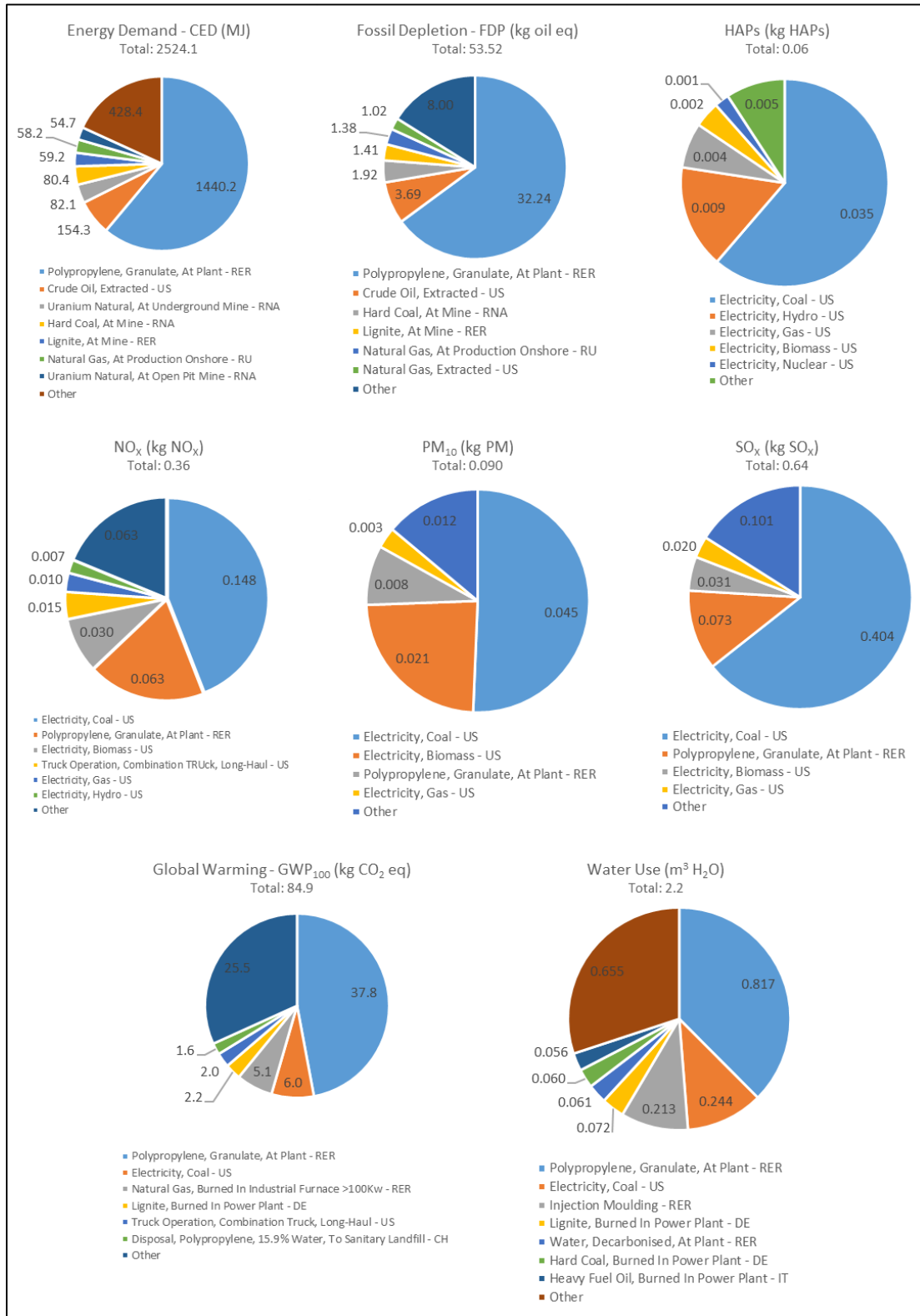


Figure 25. Emission factor results for Method 314.0

Method 314.0's associated emission factors are significantly smaller relative to the other 85 examined methods' emission factor averages. Even when compared against its own categorization (i.e., halogenated organic analytes), Method 314.0's emission factors are somewhat smaller than the methods that determine and quantify halogenate organic analytes. While Method 314.0 utilized a number of consumables, other analyzed methods utilized consumables at higher rates. The higher use of consumables by other methods was a primary reason for Method 314.0's relatively low emission factors.

4.4 Emission Factor Results

Figure 26 shows box-and-whisker plots for the eight emission factors included in the analysis. The emission factors associated with air quality (i.e., NO_x, SO_x, PM₁₀, HAPs) had similar range distributions for both organic and inorganic analytes. Halogenated organics, non-halogenated organics, and nonmetals typically had smaller ranges between their respective 25th interquartile value and 75th interquartile value when compared to inorganic metals and metalloids. For all eight emission factors, the range between the 25th interquartile value and the 75th interquartile value for inorganic nonmetals was relatively small when compared to organic analytes, and inorganic metals, and inorganic metalloids. As shown in Table 26, organics had higher values of analyzed analytes when compared to inorganics, and therefore, a higher degree of uncertainty is associated with inorganic box-and-whisker plots. The maximum values for non-halogenated organic, inorganic metals, inorganic nonmetals, and metalloids are equivalent. Their equivalence is based on Method 200.7STRA, which is capable of analyzing a wide variety of organics and inorganics and was associated with the highest overall environmental footprint of all 85 examined methods.

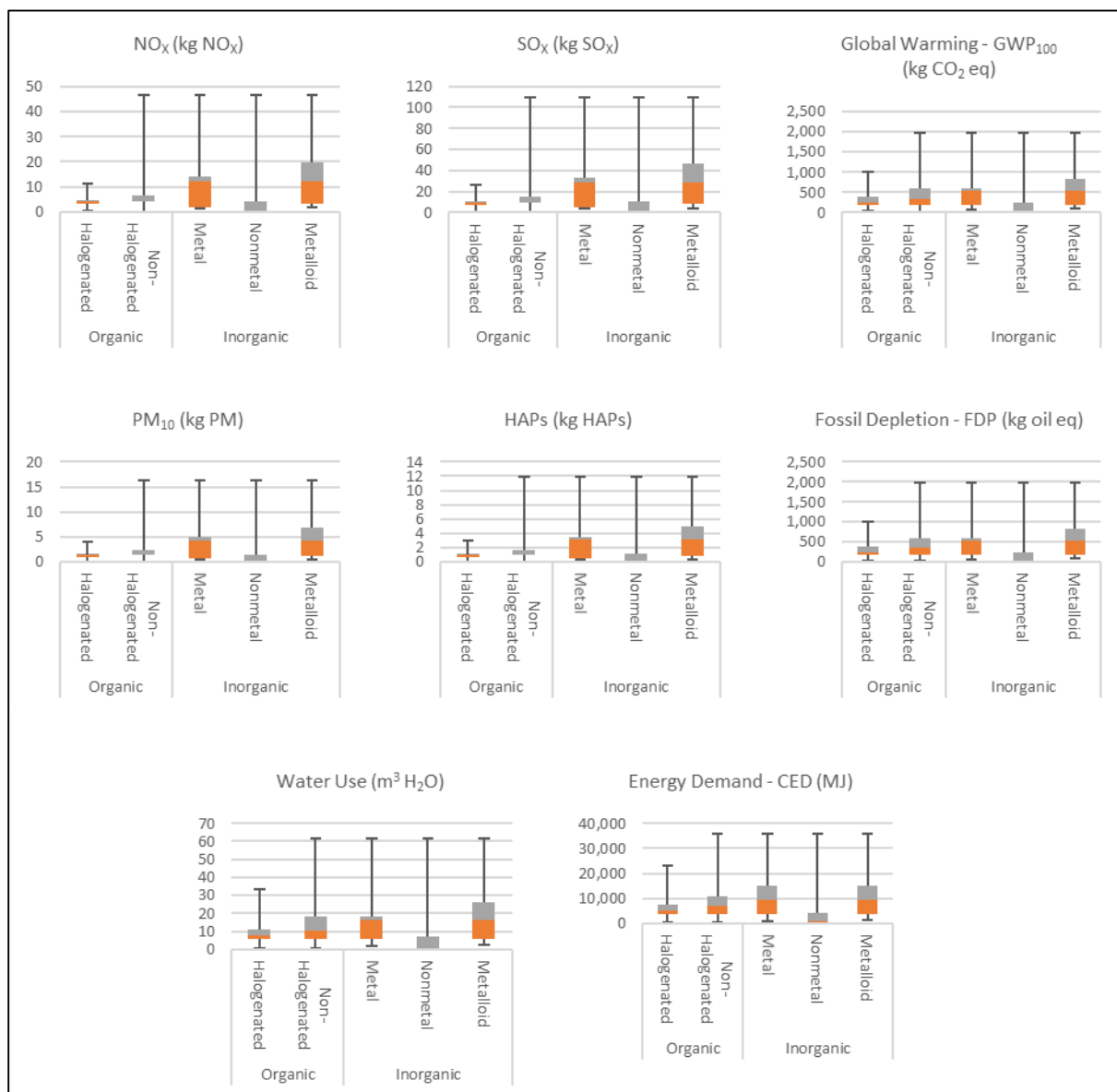


Figure 26. Box-and-whisker plots for emission factors of organic and inorganic analytes

Table 26 shows the number of analytes included the analysis (i.e., count) and the average emission factors for binned analytes. In terms of the emission factors included in this analysis, the greatest difference between organic and inorganic analytes occurred in emission factors associated with air quality (i.e., NO_x , SO_x , PM_{10} , HAPs); where all of the organic analytes' air quality emission factors were more than 50% higher than that of inorganic analytes. Organic analytes were binned as either halogenated or non-halogenated analytes. Table 26 shows that methods used to detect and quantify non-halogenated organic analytes were associated with higher emissions and/or higher overall environmental impacts when compared to halogenated organic analytes. Inorganic analytes were binned as either metal, nonmetal, or metalloid analytes.

Table 26 shows that methods used to detect and quantify inorganic analytes with metal properties (i.e., metals or metalloids) were associated with higher emissions and/or higher overall environmental impacts when compared to nonmetal inorganic analytes.

Table 26. Counts and average emission factors for organic and inorganic analytes

Organic/ Inorganic	Subcategory	Population size (n)	Functional Unit (FU)	Energy Demand (CED) MMBtu/FU	Global Warming (GWP ₁₀₀) lbs CO ₂ eq/FU	NO _x lbs/FU	SO _x lbs/FU	PM ₁₀ lbs/FU	HAPs lbs/FU	Water Use gal H ₂ O/FU
Organic	Halogenated	420	Method	6.97E+00	7.55E+02	9.09E+00	2.01E+01	2.99E+00	2.14E+00	2.40E+01
	Non-Halogenated	329	Method	9.11E+00	9.59E+02	1.42E+01	3.24E+01	4.83E+00	3.52E+00	3.26E+01
Inorganic	Metal	145	Method	9.84E+00	1.24E+03	2.71E+01	6.33E+01	9.48E+00	6.87E+00	3.85E+01
	Nonmetal	46	Method	4.44E+00	5.58E+02	1.22E+01	2.84E+01	4.26E+00	3.09E+00	1.74E+01
	Metalloid	34	Method	1.08E+01	1.38E+03	3.04E+01	7.10E+01	1.06E+01	7.71E+00	4.29E+01

Life cycle inventory results for all methods based on 100 field samples, 5 quality control samples (per 20 field samples), and 5 calibration curve samples (per 20 field samples) are shown in Table 27. The color scheme in Table 27 is normalized within each emission factor. If a method's value is shaded red within a given emission factor, then that particular method has greater impacts and/or emissions (when compared to the mean of all methods) associated with that particular emission factor. Conversely, if a method's value is shaded green within a given emission factor, then that particular method has lower impacts and/or emissions (when compared to the mean of all methods) associated with that particular emission factor. If a method's value is shaded orange within a given emission factor, then that particular method has impacts and/or emissions that are relatively similar to the average impacts and/or emissions for all methods. There are shades of green, yellow, and red, which indicate value gradation of each color.

Table 27 shows that Method 200.7STRA had the highest environmental impact and/or emissions for all eight emission factors. The relatively high environmental footprint associated with Method 200.7STRA was primarily due to the large number of consumables needed to analyze 100 field samples (with five quality control samples and five calibration points per 20 field samples). The analysis found that Method 200.7STRA required 200 low-density polyethylene (LDPE) 5mL pipette tips, 100 5-mesh sieves, and 134 polystyrene weigh boats. The volume of deionized water was an additional inventory "hotspot"; where Method 200.7STRA required nearly 60 L of deionized water to analyze 100 field samples (with five quality control samples and five calibration points per 20 field samples).

Method/ Impact	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP10	NOX (kg NOX)	SOX (kg SOX)	PM10 (kg PM)	HAPs (kg HAPs)	Water Use (m3 H2O)	Fossil Depletion – FDP (kg oil eq)
Category				0 (kg CO2 eq)						
612	Chlorinated hydrocarbons	Gas Chromatography	5.02E+03	2.15E+02	3.27E+00	7.45E+00	1.11E+00	8.33E01	8.46E+00	1.11E+02
613	2,3,7,8-tetrachlorodibenzo-p-dioxin	GC/MS	9.16E+03	4.17E+02	6.80E+00	1.56E+01	2.32E+00	1.71E+00	1.40E+01	2.04E+02
614	Organophosphorus pesticides	Gas Chromatography	5.98E+03	2.70E+02	3.22E+00	7.32E+00	1.06E+00	7.86E01	1.04E+01	1.30E+02
614.1	Organophosphorus pesticides	Gas Chromatography	6.86E+03	3.12E+02	2.96E+00	6.60E+00	9.43E01	6.84E01	1.18E+01	1.47E+02
615	Chlorinated herbicides	Gas Chromatography	1.14E+04	5.01E+02	3.26E+00	6.88E+00	9.56E01	6.40E01	2.01E+01	2.31E+02
617	Organochlorine pesticides, PCBs	Gas Chromatography	5.53E+03	2.44E+02	3.95E+00	9.03E+00	1.35E+00	1.00E+00	9.36E+00	1.23E+02
619	Triazine pesticides	Gas Chromatography	8.12E+03	3.72E+02	3.61E+00	8.04E+00	1.16E+00	8.27E01	1.38E+01	1.75E+02
622	Organophosphorus pesticides	Gas Chromatography	1.75E+03	7.77E+01	1.12E+00	2.56E+00	3.82E01	2.87E01	3.65E+00	3.72E+01
622.1	Thiophosphate pesticides	Gas Chromatography	7.63E+03	3.39E+02	2.62E+00	5.68E+00	8.08E01	5.75E01	1.30E+01	1.62E+02
624	Purgeable organics	GC/MS	8.04E+03	4.09E+02	4.74E+00	1.03E+01	1.54E+00	1.07E+00	1.12E+01	1.71E+02
625	Organic compounds	GC/MS	7.55E+03	3.57E+02	6.62E+00	1.53E+01	2.29E+00	1.69E+00	1.29E+01	1.68E+02
632	Carbamate and urea pesticides	HPLC	1.10E+04	5.53E+02	1.14E+01	2.67E+01	4.00E+00	2.92E+00	1.85E+01	2.47E+02
OIA-1677-09	Cyanide	Ligand Exchange/FIA	5.98E+02	2.44E+01	7.33E02	7.83E02	1.07E02	4.13E03	7.72E01	1.21E+01

* The analytical methods in this table are promulgated under the Clean Water Act (CWA) section 304(h)

Low impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor
Similar impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor
High impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor

AA	Atomic Adsorption
AVICP-AES	Axially Viewed Inductively Coupled Plasma - Atomic Emission Spectrometry
CVAFS	Cold-Vapor Atomic Fluorescence Spectroscopy
FIA	Flow Injection Analysis
FIDGC	Flame Ionization Detector
GC/MS	Gas Chromatography/Mass Spectrometry
HPLC	High Pressure Liquid Chromatography
HRGC	High Resolution Gas Chromatography
HRMS	High Resolution Mass Spectroscopy
ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectrometry

Table 28

and Table 29 are normalized and shaded similarly to Table 27, where the primary differentiator between the tables is the number of field samples, quality control samples, and calibration curve samples analyzed within each table.

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP100 (kg CO2 eq)	NOX (kg NOX)	SOX (kg SOX)	PM10 (kg PM)	HAPs (kg HAPs)	Water Use (m3 H2O)	Fossil Depletion – FDP (kg oil eq)
612	Chlorinated hydrocarbons	Gas Chromatography	5.02E+03	2.15E+02	3.27E+00	7.45E+00	1.11E+00	8.33E01	8.46E+00	1.11E+02
613	2,3,7,8-tetrachlorodibenzo-p-dioxin	GC/MS	9.16E+03	4.17E+02	6.80E+00	1.56E+01	2.32E+00	1.71E+00	1.40E+01	2.04E+02
614	Organophosphorus pesticides	Gas Chromatography	5.98E+03	2.70E+02	3.22E+00	7.32E+00	1.06E+00	7.86E01	1.04E+01	1.30E+02
614.1	Organophosphorus pesticides	Gas Chromatography	6.86E+03	3.12E+02	2.96E+00	6.60E+00	9.43E01	6.84E01	1.18E+01	1.47E+02
615	Chlorinated herbicides	Gas Chromatography	1.14E+04	5.01E+02	3.26E+00	6.88E+00	9.56E01	6.40E01	2.01E+01	2.31E+02
617	Organochlorine pesticides, PCBs	Gas Chromatography	5.53E+03	2.44E+02	3.95E+00	9.03E+00	1.35E+00	1.00E+00	9.36E+00	1.23E+02
619	Triazine pesticides	Gas Chromatography	8.12E+03	3.72E+02	3.61E+00	8.04E+00	1.16E+00	8.27E01	1.38E+01	1.75E+02
622	Organophosphorus pesticides	Gas Chromatography	1.75E+03	7.77E+01	1.12E+00	2.56E+00	3.82E01	2.87E01	3.65E+00	3.72E+01
622.1	Thiophosphate pesticides	Gas Chromatography	7.63E+03	3.39E+02	2.62E+00	5.68E+00	8.08E01	5.75E01	1.30E+01	1.62E+02
624	Purgeable organics	GC/MS	8.04E+03	4.09E+02	4.74E+00	1.03E+01	1.54E+00	1.07E+00	1.12E+01	1.71E+02
625	Organic compounds	GC/MS	7.55E+03	3.57E+02	6.62E+00	1.53E+01	2.29E+00	1.69E+00	1.29E+01	1.68E+02
632	Carbamate and urea pesticides	HPLC	1.10E+04	5.53E+02	1.14E+01	2.67E+01	4.00E+00	2.92E+00	1.85E+01	2.47E+02
OIA-1677-09	Cyanide	Ligand Exchange/FIA	5.98E+02	2.44E+01	7.33E02	7.83E02	1.07E02	4.13E03	7.72E01	1.21E+01

* The analytical methods in this table are promulgated under the Clean Water Act (CWA) section 304(h)

Table 28

Similar impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor	
High impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor	
AA	Atomic Adsorption
AVICP-AES	Axially Viewed Inductively Coupled Plasma - Atomic Emission Spectrometry
CVAFS	Cold-Vapor Atomic Fluorescence Spectroscopy
FIA	Flow Injection Analysis
FIDGC	Flame Ionization Detector
GC/MS	Gas Chromatography/Mass Spectrometry
HPLC	High Pressure Liquid Chromatography
HRGC	High Resolution Gas Chromatography
HRMS	High Resolution Mass Spectrometry
ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectrometry

Table 28

provides emission factors for all methods based on 1 field sample with no quality control or calibration curve samples, and Table 29 provides emission factors for all methods based on 3.5 quality control samples and 5 calibration curve samples with no field samples.

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP100 (kg CO2 eq)	NOX (kg NOX)	SOX (kg SOX)	PM10 (kg PM)	HAPs (kg HAPs)	Water Use (m3 H2O)	Fossil Depletion – FDP (kg oil eq)
612	Chlorinated hydrocarbons	Gas Chromatography	5.02E+03	2.15E+02	3.27E+00	7.45E+00	1.11E+00	8.33E01	8.46E+00	1.11E+02
613	2,3,7,8-tetrachlorodibenzo-p-dioxin	GC/MS	9.16E+03	4.17E+02	6.80E+00	1.56E+01	2.32E+00	1.71E+00	1.40E+01	2.04E+02
614	Organophosphorus pesticides	Gas Chromatography	5.98E+03	2.70E+02	3.22E+00	7.32E+00	1.06E+00	7.86E01	1.04E+01	1.30E+02
614.1	Organophosphorus pesticides	Gas Chromatography	6.86E+03	3.12E+02	2.96E+00	6.60E+00	9.43E01	6.84E01	1.18E+01	1.47E+02
615	Chlorinated herbicides	Gas Chromatography	1.14E+04	5.01E+02	3.26E+00	6.88E+00	9.56E01	6.40E01	2.01E+01	2.31E+02
617	Organochlorine pesticides, PCBs	Gas Chromatography	5.53E+03	2.44E+02	3.95E+00	9.03E+00	1.35E+00	1.00E+00	9.36E+00	1.23E+02
619	Triazine pesticides	Gas Chromatography	8.12E+03	3.72E+02	3.61E+00	8.04E+00	1.16E+00	8.27E01	1.38E+01	1.75E+02
622	Organophosphorus pesticides	Gas Chromatography	1.75E+03	7.77E+01	1.12E+00	2.56E+00	3.82E01	2.87E01	3.65E+00	3.72E+01
622.1	Thiophosphate pesticides	Gas Chromatography	7.63E+03	3.39E+02	2.62E+00	5.68E+00	8.08E01	5.75E01	1.30E+01	1.62E+02
624	Purgeable organics	GC/MS	8.04E+03	4.09E+02	4.74E+00	1.03E+01	1.54E+00	1.07E+00	1.12E+01	1.71E+02
625	Organic compounds	GC/MS	7.55E+03	3.57E+02	6.62E+00	1.53E+01	2.29E+00	1.69E+00	1.29E+01	1.68E+02
632	Carbamate and urea pesticides	HPLC	1.10E+04	5.53E+02	1.14E+01	2.67E+01	4.00E+00	2.92E+00	1.85E+01	2.47E+02
OIA-1677-09	Cyanide	Ligand Exchange/FIA	5.98E+02	2.44E+01	7.33E02	7.83E02	1.07E02	4.13E03	7.72E01	1.21E+01

* The analytical methods in this table are promulgated under the Clean Water Act (CWA) section 304(h)

Table 28

Similar impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor
High impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor

AA	Atomic Adsorption
AVICP-AES	Axially Viewed Inductively Coupled Plasma - Atomic Emission Spectrometry
CVAFS	Cold-Vapor Atomic Fluorescence Spectroscopy
FIA	Flow Injection Analysis
FIDGC	Flame Ionization Detector
GC/MS	Gas Chromatography/Mass Spectrometry
HPLC	High Pressure Liquid Chromatography
HRGC	High Resolution Gas Chromatography
HRMS	High Resolution Mass Spectrometry
ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectrometry

Table 28

and Table 29 are meant to be used in conjunction with one another to provide tailored results for a SEFA model user. For example, if a user wanted emission factors for 50 field samples, then they would take the product of 50 by each column's value for a given method in

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP100 (kg CO2 eq)	NOX (kg NOX)	SOX (kg SOX)	PM10 (kg PM)	HAPs (kg HAPs)	Water Use (m3 H2O)	Fossil Depletion – FDP (kg oil eq)
612	Chlorinated hydrocarbons	Gas Chromatography	5.02E+03	2.15E+02	3.27E+00	7.45E+00	1.11E+00	8.33E01	8.46E+00	1.11E+02
613	2,3,7,8-tetrachlorodibenzo-p-dioxin	GC/MS	9.16E+03	4.17E+02	6.80E+00	1.56E+01	2.32E+00	1.71E+00	1.40E+01	2.04E+02
614	Organophosphorus pesticides	Gas Chromatography	5.98E+03	2.70E+02	3.22E+00	7.32E+00	1.06E+00	7.86E01	1.04E+01	1.30E+02
614.1	Organophosphorus pesticides	Gas Chromatography	6.86E+03	3.12E+02	2.96E+00	6.60E+00	9.43E01	6.84E01	1.18E+01	1.47E+02
615	Chlorinated herbicides	Gas Chromatography	1.14E+04	5.01E+02	3.26E+00	6.88E+00	9.56E01	6.40E01	2.01E+01	2.31E+02
617	Organochlorine pesticides, PCBs	Gas Chromatography	5.53E+03	2.44E+02	3.95E+00	9.03E+00	1.35E+00	1.00E+00	9.36E+00	1.23E+02
619	Triazine pesticides	Gas Chromatography	8.12E+03	3.72E+02	3.61E+00	8.04E+00	1.16E+00	8.27E01	1.38E+01	1.75E+02
622	Organophosphorus pesticides	Gas Chromatography	1.75E+03	7.77E+01	1.12E+00	2.56E+00	3.82E01	2.87E01	3.65E+00	3.72E+01
622.1	Thiophosphate pesticides	Gas Chromatography	7.63E+03	3.39E+02	2.62E+00	5.68E+00	8.08E01	5.75E01	1.30E+01	1.62E+02
624	Purgeable organics	GC/MS	8.04E+03	4.09E+02	4.74E+00	1.03E+01	1.54E+00	1.07E+00	1.12E+01	1.71E+02
625	Organic compounds	GC/MS	7.55E+03	3.57E+02	6.62E+00	1.53E+01	2.29E+00	1.69E+00	1.29E+01	1.68E+02
632	Carbamate and urea pesticides	HPLC	1.10E+04	5.53E+02	1.14E+01	2.67E+01	4.00E+00	2.92E+00	1.85E+01	2.47E+02
OIA-1677-09	Cyanide	Ligand Exchange/FIA	5.98E+02	2.44E+01	7.33E02	7.83E02	1.07E02	4.13E03	7.72E01	1.21E+01

* The analytical methods in this table are promulgated under the Clean Water Act (CWA) section 304(h)

Table 28

Similar impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor	
High impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor	
AA	Atomic Adsorption
AVICP-AES	Axially Viewed Inductively Coupled Plasma - Atomic Emission Spectrometry
CVAFS	Cold-Vapor Atomic Fluorescence Spectroscopy
FIA	Flow Injection Analysis
FIDGC	Flame Ionization Detector
GC/MS	Gas Chromatography/Mass Spectrometry
HPLC	High Pressure Liquid Chromatography
HRGC	High Resolution Gas Chromatography
HRMS	High Resolution Mass Spectrometry
ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectrometry

Table 28

. These values would represent the emission factors for 50 field samples, with the results not including any impacts related to quality control samples and calibration curve samples. Table 29 can be used to calculate emission factors related to quality control samples and calibration curve samples, where each emission factor is based on a single analysis batch. If 20 field samples were assumed per analysis batch, then 50 field samples would require three analysis batches in order to meet quality control and calibration curve requirements. Hence, to calculate the emission factors related to quality control samples and calibration curve samples, the user would multiply three by each column's value for a given method in Table 29. Finally, the calculated results from

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP100 (kg CO ₂ eq)	NOX (kg NOX)	SOX (kg SOX)	PM10 (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
612	Chlorinated hydrocarbons	Gas Chromatography	5.02E+03	2.15E+02	3.27E+00	7.45E+00	1.11E+00	8.33E01	8.46E+00	1.11E+02
613	2,3,7,8-tetrachlorodibenzo-p-dioxin	GC/MS	9.16E+03	4.17E+02	6.80E+00	1.56E+01	2.32E+00	1.71E+00	1.40E+01	2.04E+02
614	Organophosphorus pesticides	Gas Chromatography	5.98E+03	2.70E+02	3.22E+00	7.32E+00	1.06E+00	7.86E01	1.04E+01	1.30E+02
614.1	Organophosphorus pesticides	Gas Chromatography	6.86E+03	3.12E+02	2.96E+00	6.60E+00	9.43E01	6.84E01	1.18E+01	1.47E+02
615	Chlorinated herbicides	Gas Chromatography	1.14E+04	5.01E+02	3.26E+00	6.88E+00	9.56E01	6.40E01	2.01E+01	2.31E+02
617	Organochlorine pesticides, PCBs	Gas Chromatography	5.53E+03	2.44E+02	3.95E+00	9.03E+00	1.35E+00	1.00E+00	9.36E+00	1.23E+02
619	Triazine pesticides	Gas Chromatography	8.12E+03	3.72E+02	3.61E+00	8.04E+00	1.16E+00	8.27E01	1.38E+01	1.75E+02
622	Organophosphorus pesticides	Gas Chromatography	1.75E+03	7.77E+01	1.12E+00	2.56E+00	3.82E01	2.87E01	3.65E+00	3.72E+01
622.1	Thiophosphate pesticides	Gas Chromatography	7.63E+03	3.39E+02	2.62E+00	5.68E+00	8.08E01	5.75E01	1.30E+01	1.62E+02
624	Purgeable organics	GC/MS	8.04E+03	4.09E+02	4.74E+00	1.03E+01	1.54E+00	1.07E+00	1.12E+01	1.71E+02
625	Organic compounds	GC/MS	7.55E+03	3.57E+02	6.62E+00	1.53E+01	2.29E+00	1.69E+00	1.29E+01	1.68E+02

Table 28

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP100 (kg CO2 eq)	NOX (kg NOX)	SOX (kg SOX)	PM10 (kg PM)	HAPs (kg HAPs)	Water Use (m3 H2O)	Fossil Depletion – FDP (kg oil eq)
632	Carbamate and urea pesticides	HPLC	1.10E+04	5.53E+02	1.14E+01	2.67E+01	4.00E+00	2.92E+00	1.85E+01	2.47E+02
OIA- 1677- 09	Cyanide	Ligand Exchange/ FIA	5.98E+02	2.44E+01	7.33E02	7.83E02	1.07E02	4.13E03	7.72E01	1.21E+01

* The analytical methods in this table are promulgated under the Clean Water Act (CWA) section 304(h)

Table 28

Low impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor
Similar impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor
High impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor

AA	Atomic Adsorption
AVICP-AES	Axially Viewed Inductively Coupled Plasma - Atomic Emission Spectrometry
CVAFS	Cold-Vapor Atomic Fluorescence Spectroscopy
FIA	Flow Injection Analysis
FIDGC	Flame Ionization Detector
GC/MS	Gas Chromatography/Mass Spectrometry
HPLC	High Pressure Liquid Chromatography
HRGC	High Resolution Gas Chromatography
HRMS	High Resolution Mass Spectroscopy
ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectrometry

Table 28

and Table 29 would be summed to provide emissions for a method, given a specific number of field samples, and quality control and calibration curve requirements.

It should be noted that 3.5 quality control samples were assumed because that value represents the midpoint within an analysis batch. For example, it was assumed that two quality control samples are typically analyzed for the first five field samples. It was assumed that beyond five field samples and up to 20 field samples, one quality control sample is required for each additional five field samples. These assumptions yielded the following quality control specifications: 1 to 5 field samples – 2 quality control samples (40% of 5), 6 to 10 field samples – 3 quality control samples (60% of 5), 11 to 15 field samples – 4 quality control samples (80% of 5), and 16 to 20 field samples – 5 quality control samples (100% of 5). Given the ranges (i.e., 1 to 5, 6 to 10, 11 to 15, 16 to 20) and their corresponding percentages (i.e., 40%, 60%, 80%, 100%, respectively), a weighted average of 70% was obtained which corresponded with 3.5 quality control samples (i.e., $70\% \times 5 = 3.5$). This midpoint value was used because it represented the most accurate depiction of quality control and calibration curve sampling activities given ranging numbers of field samples that may or may not represent an entire analysis batch.

Table 27. Emission factors for all methods based on 100 field samples, 5 quality control samples per 20 field samples (or 25 quality control samples), and 5 calibration curve samples per 20 field samples (or 25 calibration curve samples)

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
120.1	Conductance	Conductivity Meter	3.01E+03	1.58E+02	3.48E+00	8.14E+00	1.22E+00	8.85E-01	4.89E+00	6.76E+01
130.1	Hardness Total	Spectrophotometer	1.78E+03	5.74E+01	2.08E-01	3.42E-01	4.87E-02	2.93E-02	1.54E+00	3.76E+01
150.2	pH	pH Meter	1.63E+02	5.37E+00	2.25E-02	3.94E-02	5.71E-03	3.65E-03	1.44E-01	3.45E+00
160.4	Residue, Volatile	Muffle Furnace	1.93E+03	1.05E+02	2.44E+00	5.69E+00	8.55E-01	6.20E-01	3.21E+00	4.38E+01
1613BA	Chlorinated Dioxins, Furans	HRGC/HRMS	2.31E+04	1.08E+03	4.19E+00		7.82E-01	4.01E-01	3.04E+01	4.69E+02
1613BS	Chlorinated Dioxins, Furans	HRGC/HRMS	1.10E+04	4.59E+02	3.01E+00	5.79E+00	8.45E-01	6.02E-01	1.55E+01	2.35E+02
1613BT	Chlorinated Dioxins, Furans	HRGC/HRMS	1.80E+04	7.65E+02	1.17E+01	2.66E+01	3.95E+00	2.94E+00	2.60E+01	4.03E+02
1624B	Organic compounds	GC/MS	7.54E+03	3.90E+02	4.69E+00	1.02E+01	1.54E+00	1.06E+00	1.05E+01	1.61E+02
1625B	Organic compounds	GC/MS	2.42E+04	9.11E+02	6.58E+00	1.36E+01	1.99E+00	1.50E+00	3.58E+01	5.34E+02
1627	Mine Drainage Quality	Column Apparatus	2.21E+04	6.80E+02	1.48E+00	1.33E+00	1.87E-01	2.36E-01	2.75E+01	4.94E+02
1631E	Mercury	CVAFS	1.53E+04	5.23E+02	3.45E+00	6.93E+00	1.02E+00	6.98E-01	1.43E+01	3.26E+02
1664A	HEM, SGT-HEM	Extraction/ Gravimetry	1.28E+04	6.23E+02	1.40E+01	3.27E+01	4.91E+00	3.58E+00	2.05E+01	2.81E+02
1664B	HEM, SGT-HEM	Extraction/ Gravimetry	1.28E+04	6.23E+02	1.40E+01	3.27E+01	4.91E+00	3.58E+00	2.05E+01	2.81E+02
180.1	Turbidity	Nephelometry	2.67E+02	1.34E+01	1.74E-01	3.80E-01	5.67E-02	3.98E-02	3.81E-01	5.66E+00
200.2 ATRA	Sample Preparation Procedure for Spectrochemical Determination of Total Recoverable Elements	ICP-AES	3.86E+03	1.71E+02	1.89E+00	4.30E+00	6.39E-01	5.39E-01	1.39E+01	7.68E+01
200.2 STRA	Sample Preparation Procedure for Spectrochemical Determination of Total Recoverable Elements	ICP-AES	3.66E+03	1.89E+02	3.89E+00	9.06E+00	1.36E+00	9.85E-01	5.90E+00	8.17E+01
200.5	Trace Elements in Drinking Water	AVICP-AES	7.98E+03	3.77E+02	2.06E+00	3.33E+00	4.86E-01	2.80E-01	1.04E+01	1.57E+02

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
200.7ADA	Metals and Trace Elements in Water and Wastes	ICP-AES	1.51E+04	8.39E+02	1.96E+01	4.60E+01	6.90E+00	5.01E+00	2.63E+01	3.41E+02

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
200.7 ATRA	Metals and Trace Elements in Water and Wastes	ICP-AES	1.62E+04	9.09E+02	2.13E+01	5.01E+01	7.51E+00	5.45E+00	2.85E+01	3.68E+02
200.7 STRA	Metals and Trace Elements in Water and Wastes	ICP-AES	3.58E+04	1.99E+03	4.65E+01	1.09E+02	1.64E+01	1.19E+01	6.21E+01	8.11E+02
200.8ADA	Trace Elements in Water and Wastes	ICP-MS	9.40E+03	5.23E+02	1.22E+01	2.85E+01	4.28E+00	3.11E+00	1.63E+01	2.13E+02
200.8 ATRA	Trace Elements in Water and Wastes	ICP-MS	1.06E+04	5.95E+02	1.39E+01	3.26E+01	4.89E+00	3.55E+00	1.87E+01	2.41E+02
200.8 STRA	Trace Elements in Water and Wastes	ICP-MS	1.07E+04	5.95E+02	1.39E+01	3.26E+01	4.89E+00	3.55E+00	1.87E+01	2.41E+02
200.9	Trace Elements in Drinking Water	GFAA	5.92E+03	2.64E+02	4.72E+00	1.08E+01	1.62E+00	1.17E+00	8.37E+00	1.26E+02
206.5	Arsenic	AA	2.61E+03	1.46E+02	3.37E+00	7.90E+00	1.18E+00	8.60E-01	4.54E+00	5.91E+01
218.6	Hexavalent Chromium	Ion Chromatography	1.17E+03	3.25E+01	6.22E-01	1.37E+00	2.07E-01	1.46E-01	1.59E+00	2.03E+01
231.2	Gold	AA	1.57E+03	8.70E+01	2.01E+00	4.71E+00	7.06E-01	5.13E-01	2.80E+00	3.54E+01
235.2	Iridium	AA	1.57E+03	8.70E+01	2.01E+00	4.71E+00	7.06E-01	5.13E-01	2.80E+00	3.54E+01
245.1	Mercury	CVAAS	7.72E+03	4.23E+02	9.65E+00	2.26E+01	3.39E+00	2.46E+00	1.32E+01	1.75E+02
245.2	Mercury	AA	1.13E+03	6.31E+01	1.47E+00	3.46E+00	5.18E-01	3.76E-01	1.99E+00	2.56E+01
245.7	Mercury	CVAFS	1.60E+04	5.65E+02	4.56E+00	9.56E+00	1.42E+00	9.81E-01	1.54E+01	3.43E+02
252.2	Osmium	AA	1.57E+03	8.70E+01	2.01E+00	4.71E+00	7.06E-01	5.13E-01	2.80E+00	3.54E+01
253.2	Palladium	AA	1.57E+03	8.70E+01	2.01E+00	4.71E+00	7.06E-01	5.13E-01	2.80E+00	3.54E+01
255.2	Platinum	AA	1.57E+03	8.70E+01	2.01E+00	4.71E+00	7.06E-01	5.13E-01	2.80E+00	3.54E+01
265.2	Rhodium	AA	1.57E+03	8.70E+01	2.01E+00	4.71E+00	7.06E-01	5.13E-01	2.80E+00	3.54E+01
267.2	Ruthenium	AA	1.57E+03	8.69E+01	2.01E+00	4.71E+00	7.06E-01	5.13E-01	2.80E+00	3.54E+01
279.2	Thallium	AA	1.57E+03	8.70E+01	2.01E+00	4.71E+00	7.06E-01	5.13E-01	2.80E+00	3.54E+01

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
283.2	Titanium	AA	1.57E+03	8.70E+01	2.01E+00	4.71E+00	7.06E-01	5.13E-01	2.80E+00	3.54E+01
289.2	Zinc	AA	1.57E+03	8.70E+01	2.01E+00	4.71E+00	7.06E-01	5.13E-01	2.80E+00	3.54E+01
300	Inorganic Anions	Ion Chromatography	5.93E+02	2.48E+01	3.45E-01	7.82E-01	1.17E-01	8.39E-02	8.01E-01	1.28E+01
300.1	Inorganic Anions	Ion Chromatography	7.81E+02	2.93E+01	3.07E-01	6.71E-01	9.99E-02	7.05E-02	8.36E-01	1.67E+01
310.2	Alkalinity	Autoanalyzer	1.84E+03	6.07E+01	3.18E-01	6.01E-01	8.80E-02	5.82E-02	1.63E+00	3.90E+01
314	Perchlorate	Ion Chromatography	2.52E+03	8.49E+01	3.62E-01	6.42E-01	9.32E-02	5.84E-02	2.20E+00	5.35E+01
335.4	Cyanide	Semi-automated Colorimetry	9.73E+02	4.96E+01	9.54E-01	2.22E+00	3.32E-01	2.42E-01	1.76E+00	2.14E+01
350.1	Ammonia Nitrogen	Semi-automated Colorimetry	2.55E+03	1.12E+02	3.35E-01	5.86E-01	6.35E-02	2.37E-02	5.06E+00	4.75E+01
351.1	Kjeldahl Nitrogen	Autoanalyzer	3.01E+02	1.29E+01	6.85E-02	1.38E-01	1.91E-02	1.28E-02	5.58E-01	6.21E+00
351.2	Kjeldahl Nitrogen	Semi-automated Colorimetry	7.96E+03	4.26E+02	3.39E+00	7.57E+00	1.06E+00	6.99E-01	1.51E+01	1.66E+02
352.1	Nitrogen, Nitrate	Spectrophotometer	3.55E+03	1.95E+02	4.33E+00	1.01E+01	1.52E+00	1.10E+00	6.02E+00	7.98E+01

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
353.2	Nitrite singly	Automated Colorimetry	2.63E+02	1.38E+01	2.82E-01	6.60E-01	9.86E-02	7.18E-02	5.34E-01	5.81E+00
365.1	Phosphorus	Semi-automated Colorimetry	1.47E+02	6.39E+00	2.70E-02	5.47E-02	7.28E-03	6.05E-03	4.43E-01	2.89E+00
365.3	Phosphorus	Spectrophotometer	4.43E+03	2.43E+02	5.56E+00	1.30E+01	1.95E+00	1.42E+00	7.63E+00	1.00E+02
365.4	Phosphorus	Autoanalyzer	1.81E+03	1.01E+02	2.34E+00	5.49E+00	8.23E-01	5.98E-01	3.21E+00	4.09E+01
375.2	Sulfate	Automated Colorimetry	1.49E+03	6.68E+01	3.62E-01	6.17E-01	8.98E-02	5.45E-02	1.78E+00	3.06E+01
410.3	Chemical Oxygen Demand	Titration	2.04E+04	1.13E+03	2.63E+01	6.16E+01	9.24E+00	6.71E+00	3.60E+01	4.61E+02
410.4	Chemical Oxygen Demand	Semi-automated Colorimetry	6.19E+03	3.46E+02	7.78E+00	1.82E+01	2.73E+00	1.98E+00	1.08E+01	1.40E+02
420.1CE	Phenolics	Spectrophotometer	1.78E+03	8.94E+01	1.71E+00	3.99E+00	5.98E-01	4.44E-01	4.42E+00	3.83E+01
420.1DP	Phenolics	Spectrophotometer	1.59E+03	8.25E+01	1.70E+00	3.98E+00	5.96E-01	4.37E-01	3.28E+00	3.50E+01
420.4	Phenolics	Semi-automated Colorimetry	7.61E+03	2.40E+02	7.46E-01	1.03E+00	1.50E-01	1.44E-01	9.69E+00	1.70E+02

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
525.1	Organic Compounds in Drinking Water	GC/MS	3.96E+03	1.99E+02	4.01E+00	9.33E+00	1.40E+00	1.02E+00	7.01E+00	8.87E+01
525.2	Organic Compounds in Drinking Water	GC/MS	3.96E+03	1.99E+02	4.01E+00	9.33E+00	1.40E+00	1.02E+00	7.01E+00	8.87E+01
601	Purgeable Halocarbons	Gas Chromatography	3.45E+03	1.91E+02	1.33E+00	2.76E+00	4.41E-01	2.76E-01	4.44E+00	7.47E+01
602	Purgeable aromatics	Gas Chromatography	3.23E+03	1.44E+02	1.30E+00	2.68E+00	4.21E-01	2.80E-01	3.25E+00	7.09E+01
603	Acrolein, Acrylonitrile	Gas Chromatography	5.37E+03	2.70E+02	1.86E+00	3.55E+00	5.38E-01	3.37E-01	6.92E+00	1.11E+02
604	Phenols	FIDGC	6.63E+03	3.10E+02	3.28E+00	7.36E+00	1.07E+00	7.72E-01	1.21E+01	1.42E+02
605	Benzidines	HPLC	1.09E+04	5.38E+02	1.07E+01	2.47E+01	3.71E+00	2.71E+00	1.80E+01	2.45E+02
606	Phthalate esters	Gas Chromatography	5.16E+03	2.23E+02	3.44E+00	7.85E+00	1.17E+00	8.76E-01	8.70E+00	1.14E+02
607	Nitrosamines	Gas Chromatography	6.33E+03	2.96E+02	3.11E+00	6.94E+00	1.01E+00	7.28E-01	1.13E+01	1.36E+02
608	Organochlorine pesticides, PCBs	Gas Chromatography	5.41E+03	2.37E+02	3.78E+00	8.64E+00	1.29E+00	9.62E-01	9.14E+00	1.20E+02
608.1	Organochlorine pesticides	Gas Chromatography	5.02E+03	2.15E+02	3.27E+00	7.45E+00	1.11E+00	8.33E-01	8.46E+00	1.11E+02
608.2	Organochlorine pesticides	Gas Chromatography	5.02E+03	2.16E+02	3.28E+00	7.45E+00	1.11E+00	8.33E-01	8.47E+00	1.11E+02
609	Nitroaromatics, Isophorone	Gas Chromatography	5.22E+03	2.24E+02	3.45E+00	7.84E+00	1.17E+00	8.77E-01	8.73E+00	1.16E+02
610	Polynuclear aromatic hydrocarbons	HPLC, GC	5.77E+03	2.57E+02	4.26E+00	9.76E+00	1.46E+00	1.08E+00	9.77E+00	1.28E+02
611	Haloethers	Gas Chromatography	5.45E+03	2.41E+02	3.94E+00	9.02E+00	1.35E+00	1.00E+00	8.98E+00	1.21E+02

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
612	Chlorinated hydrocarbons	Gas Chromatography	5.02E+03	2.15E+02	3.27E+00	7.45E+00	1.11E+00	8.33E-01	8.46E+00	1.11E+02
613	2,3,7,8tetrachlorodibenzo- p- dioxin	GC/MS	9.16E+03	4.17E+02	6.80E+00	1.56E+01	2.32E+00	1.71E+00	1.40E+01	2.04E+02
614	Organophosphorus	Gas Chromatography	5.98E+03	2.70E+02	3.22E+00	7.32E+00	1.06E+00	7.86E-01	1.04E+01	1.30E+02

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
	pesticides									
614.1	Organophosphorus pesticides	Gas Chromatography	6.86E+03	3.12E+02	2.96E+00	6.60E+00	9.43E-01	6.84E-01	1.18E+01	1.47E+02
615	Chlorinated herbicides	Gas Chromatography	1.14E+04	5.01E+02	3.26E+00	6.88E+00	9.56E-01	6.40E-01	2.01E+01	2.31E+02
617	Organochlorine pesticides, PCBs	Gas Chromatography	5.53E+03	2.44E+02	3.95E+00	9.03E+00	1.35E+00	1.00E+00	9.36E+00	1.23E+02
619	Triazine pesticides	Gas Chromatography	8.12E+03	3.72E+02	3.61E+00	8.04E+00	1.16E+00	8.27E-01	1.38E+01	1.75E+02
622	Organophosphorus pesticides	Gas Chromatography	1.75E+03	7.77E+01	1.12E+00	2.56E+00	3.82E-01	2.87E-01	3.65E+00	3.72E+01
622.1	Thiophosphate pesticides	Gas Chromatography	7.63E+03	3.39E+02	2.62E+00	5.68E+00	8.08E-01	5.75E-01	1.30E+01	1.62E+02
624	Purgeable organics	GC/MS	8.04E+03	4.09E+02	4.74E+00	1.03E+01	1.54E+00	1.07E+00	1.12E+01	1.71E+02
625	Organic compounds	GC/MS	7.55E+03	3.57E+02	6.62E+00	1.53E+01	2.29E+00	1.69E+00	1.29E+01	1.68E+02
632	Carbamate and urea pesticides	HPLC	1.10E+04	5.53E+02	1.14E+01	2.67E+01	4.00E+00	2.92E+00	1.85E+01	2.47E+02
OIA-1677-09	Cyanide	Ligand Exchange/ FIA	5.98E+02	2.44E+01	7.33E-02	7.83E-02	1.07E-02	4.13E-03	7.72E-01	1.21E+01

* The analytical methods in this table are promulgated under the Clean Water Act (CWA) section 304(h)

Low impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor
Similar impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor
High impacts and/or emissions when compared to the average impacts and/or emissions of all methods within a given emission factor

AA	Atomic Adsorption
AVICP-AES	Axially Viewed Inductively Coupled Plasma - Atomic Emission Spectrometry
CVAFS	Cold-Vapor Atomic Fluorescence Spectroscopy
FIA	Flow Injection Analysis
FIDGC	Flame Ionization Detector
GC/MS	Gas Chromatography/Mass Spectrometry
HPLC	High Pressure Liquid Chromatography
HRGC	High Resolution Gas Chromatography
HRMS	High Resolution Mass Spectroscopy
ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectrometry

Table 28. Emission factors for all methods based on 1 field sample with no quality control or calibration curve samples

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
120.1	Conductance	Conductivity Meter	6.71E+00	2.76E-01	3.49E-03	7.84E-03	1.17E-03	8.60E-04	1.22E-02	1.42E-01
130.1	Hardness Total	Spectrophotometer	4.62E+01	2.25E+00	6.07E-03	1.09E-02	1.17E-03	6.62E-04	1.04E-01	9.25E-01
150.2	pH	pH Meter	1.27E+00	4.19E-02	1.74E-04	3.04E-04	4.41E-05	2.88E-05	1.16E-03	2.69E-02
160.4	Residue, Volatile	Muffle Furnace	1.93E+01	1.05E+00	2.44E-02	5.69E-02	8.55E-03	6.20E-03	3.21E-02	4.38E-01
1613BA	Chlorinated Dioxins, Furans	HRGC/HRMS	2.33E+02	1.09E+01	4.23E-02	5.62E-02	7.93E-03	4.08E-03	3.08E-01	4.75E+00
1613BS	Chlorinated Dioxins, Furans	HRGC/HRMS	1.12E+02	4.69E+00	3.05E-02	5.87E-02	8.56E-03	6.09E-03	1.59E-01	2.40E+00
1613BT	Chlorinated Dioxins, Furans	HRGC/HRMS	1.83E+02	7.76E+00	1.17E-01	2.67E-01	3.97E-02	2.95E-02	2.64E-01	4.08E+00
1624B	Organic compounds	GC/MS	6.13E+01	3.20E+00	3.22E-02	6.78E-02	1.02E-02	6.93E-03	8.47E-02	1.29E+00
1625B	Organic compounds	GC/MS	2.35E+02	8.61E+00	5.16E-02	1.02E-01	1.48E-02	1.13E-02	3.43E-01	5.17E+00

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
1627	Mine Drainage Quality	Column Apparatus	2.21E+02	6.81E+00	1.49E-02	1.34E-02	1.88E-03	2.37E-03	2.75E-01	4.95E+00
1631E	Mercury	CVAFS	2.66E+02	1.06E+01	4.32E-02	7.52E-02	1.05E-02	1.11E-02	5.14E-01	5.19E+00
1664A	HEM, SGT-HEM	Extraction/ Gravimetry	1.81E+02	8.93E+00	1.95E-01	4.54E-01	6.80E-02	4.96E-02	2.98E-01	3.99E+00
1664B	HEM, SGT-HEM	Extraction/ Gravimetry	1.81E+02	8.93E+00	1.95E-01	4.54E-01	6.80E-02	4.96E-02	2.98E-01	3.99E+00
180.1	Turbidity	Nephelometry	4.55E+00	1.92E-01	1.58E-03	3.27E-03	4.82E-04	3.43E-04	7.17E-03	9.47E-02
200.2 ATRA	Sample Preparation Procedure for Spectrochemical Determination of Total Recoverable Elements	ICP-AES	7.77E+01	4.72E+00	2.59E-02	4.80E-02	7.11E-03	7.02E-03	2.39E-01	1.49E+00
200.2 STRA	Sample Preparation Procedure for Spectrochemical Determination of Total Recoverable Elements	ICP-AES	7.58E+01	4.90E+00	4.59E-02	9.56E-02	1.43E-02	1.15E-02	1.59E-01	1.54E+00
200.5	Trace Elements in Drinking Water	AVICP-AES	1.15E+02	6.21E+00	2.49E-02	3.59E-02	5.19E-03	3.90E-03	2.35E-01	2.24E+00
200.7ADA	Metals and Trace Elements in Water and Wastes	ICP-AES	1.49E+02	9.38E+00	1.33E-01	2.98E-01	4.46E-02	3.34E-02	3.52E-01	3.18E+00
200.7 ATRA	Metals and Trace Elements in Water and Wastes	ICP-AES	1.60E+02	1.01E+01	1.50E-01	3.38E-01	5.06E-02	3.78E-02	3.75E-01	3.44E+00

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
200.7 STRA	Metals and Trace Elements in Water and Wastes	ICP-AES	3.55E+02	2.09E+01	4.02E-01	9.28E-01	1.39E-01	1.02E-01	7.11E-01	7.87E+00

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
200.8ADA	Trace Elements in Water and Wastes	ICP-MS	1.41E+02	8.83E+00	1.30E-01	2.93E-01	4.38E-02	3.28E-02	2.84E-01	3.03E+00
200.8 ATRA	Trace Elements in Water and Wastes	ICP-MS	1.53E+02	9.54E+00	1.48E-01	3.33E-01	4.99E-02	3.73E-02	3.09E-01	3.30E+00
200.8 STRA	Trace Elements in Water and Wastes	ICP-MS	1.53E+02	9.55E+00	1.48E-01	3.33E-01	4.99E-02	3.73E-02	3.10E-01	3.31E+00
200.9	Trace Elements in Drinking Water	GFAA	9.60E+01	5.76E+00	4.55E-02	9.20E-02	1.37E-02	1.14E-02	2.65E-01	1.88E+00
206.5	Arsenic	AA	2.68E+01	1.49E+00	3.38E-02	7.92E-02	1.19E-02	8.62E-03	4.66E-02	6.07E-01
218.6	Hexavalent Chromium	Ion Chromatography	1.97E+01	8.34E-01	5.65E-03	1.17E-02	1.72E-03	1.30E-03	3.17E-02	4.26E-01
231.2	Gold	AA	1.46E+01	7.79E-01	1.57E-02	3.67E-02	5.49E-03	4.01E-03	2.89E-02	3.22E-01
235.2	Iridium	AA	1.46E+01	7.79E-01	1.57E-02	3.67E-02	5.49E-03	4.01E-03	2.89E-02	3.22E-01
245.1	Mercury	CVAAS	1.16E+02	7.39E+00	1.04E-01	2.33E-01	3.47E-02	2.50E-02	1.96E-01	2.56E+00
245.2	Mercury	AA	2.82E+01	1.53E+00	1.70E-02	3.85E-02	5.59E-03	4.06E-03	6.83E-02	5.89E-01
245.7	Mercury	CVAFS	4.31E+02	2.07E+01	3.95E-01	9.15E-01	1.37E-01	9.91E-02	6.40E-01	9.54E+00
252.2	Osmium	AA	1.47E+01	7.97E-01	1.58E-02	3.67E-02	5.49E-03	4.01E-03	2.90E-02	3.25E-01
253.2	Palladium	AA	1.46E+01	7.79E-01	1.57E-02	3.67E-02	5.49E-03	4.01E-03	2.89E-02	3.22E-01
255.2	Platinum	AA	1.46E+01	7.79E-01	1.57E-02	3.67E-02	5.49E-03	4.01E-03	2.89E-02	3.22E-01
265.2	Rhodium	AA	1.46E+01	7.79E-01	1.57E-02	3.67E-02	5.49E-03	4.01E-03	2.89E-02	3.22E-01
267.2	Ruthenium	AA	1.48E+01	7.78E-01	1.57E-02	3.67E-02	5.50E-03	4.03E-03	3.01E-02	3.26E-01
279.2	Thallium	AA	1.46E+01	7.79E-01	1.57E-02	3.67E-02	5.49E-03	4.01E-03	2.89E-02	3.22E-01
283.2	Titanium	AA	1.46E+01	7.79E-01	1.57E-02	3.67E-02	5.49E-03	4.01E-03	2.89E-02	3.22E-01
289.2	Zinc	AA	1.46E+01	7.79E-01	1.57E-02	3.67E-02	5.49E-03	4.01E-03	2.89E-02	3.22E-01
300	Inorganic Anions	Ion Chromatography	2.44E+01	9.97E-01	4.39E-03	8.92E-03	1.27E-03	1.30E-03	1.21E-01	4.73E-01
300.1	Inorganic Anions	Ion Chromatography	1.30E+01	5.07E-01	3.15E-03	6.57E-03	9.55E-04	7.45E-04	3.22E-02	2.67E-01
310.2	Alkalinity	Autoanalyzer	1.84E+03	6.07E+01	3.18E-01	6.01E-01	8.80E-02	5.82E-02	1.63E+00	3.90E+01
314	Perchlorate	Ion Chromatography	8.80E+01	3.95E+00	1.07E-02	1.84E-02	2.02E-03	8.39E-04	1.30E-01	1.81E+00
335.4	Cyanide	Semi-automated Colorimetry	7.22E+01	3.81E+00	1.69E-02	3.51E-02	4.44E-03	3.01E-03	1.99E-01	1.44E+00
350.1	Ammonia Nitrogen	Semi-automated Colorimetry	6.89E+01	3.17E+00	8.04E-03	1.36E-02	1.46E-03	1.06E-03	2.00E-01	1.33E+00
351.1	Kjeldahl Nitrogen	Autoanalyzer	1.53E+02	7.44E+00	1.87E-02	3.09E-02	3.16E-03	1.72E-03	4.12E-01	3.04E+00
351.2	Kjeldahl Nitrogen	Semi-automated Colorimetry	1.30E+02	6.96E+00	4.05E-02	8.73E-02	1.17E-02	7.55E-03	3.09E-01	2.61E+00
352.1	Nitrogen, Nitrate	Spectrophotometer	6.55E+01	3.55E+00	4.76E-02	1.08E-01	1.59E-02	1.14E-02	1.40E-01	1.39E+00

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
353.2	Nitrite singly	Automated Colorimetry	2.26E+01	1.07E+00	5.28E-03	1.27E-02	1.55E-03	1.18E-03	7.63E-02	4.51E-01
Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
365.1	Phosphorus	Semi-automated Colorimetry	2.28E+01	1.04E+00	2.69E-03	4.78E-03	5.26E-04	4.22E-04	5.93E-02	4.59E-01
365.3	Phosphorus	Spectrophotometer	7.07E+01	3.76E+00	5.89E-02	1.36E-01	2.01E-02	1.46E-02	1.44E-01	1.53E+00
365.4	Phosphorus	Autoanalyzer	4.63E+01	2.41E+00	2.69E-02	6.11E-02	8.86E-03	6.40E-03	1.08E-01	9.75E-01
375.2	Sulfate	Automated Colorimetry	5.43E+01	2.01E+00	5.62E-03	8.14E-03	1.09E-03	1.09E-03	1.46E-01	1.11E+00
410.3	Chemical Oxygen Demand	Titration	3.23E+02	1.88E+01	2.31E-01	5.33E-01	7.71E-02	5.42E-02	9.75E-01	6.78E+00
410.4	Chemical Oxygen Demand	Semi-automated Colorimetry	2.21E+02	1.32E+01	9.82E-02	2.20E-01	3.00E-02	1.98E-02	4.80E-01	4.51E+00
420.1CE	Phenolics	#N/A	3.60E+01	1.79E+00	1.93E-02	4.39E-02	6.39E-03	4.75E-03	9.80E-02	7.41E-01
420.1DP	Phenolics	#N/A	3.41E+01	1.72E+00	1.92E-02	4.37E-02	6.37E-03	4.68E-03	8.66E-02	7.08E-01
420.4	Phenolics	Semi-automated Colorimetry	8.34E+01	2.65E+00	6.91E-03	8.42E-03	1.20E-03	1.27E-03	1.16E-01	1.85E+00
525.1	Organic Compounds in Drinking Water	GC/MS	3.98E+01	1.77E+00	2.66E-02	6.05E-02	8.99E-03	6.59E-03	6.63E-02	8.86E-01
525.2	Organic Compounds in Drinking Water	GC/MS	3.98E+01	1.77E+00	2.66E-02	6.05E-02	8.99E-03	6.59E-03	6.63E-02	8.86E-01
601	Purgeable Halocarbons	Gas Chromatography	2.92E+01	1.67E+00	9.22E-03	1.83E-02	3.01E-03	1.76E-03	3.78E-02	6.33E-01
602	Purgeable aromatics	Gas Chromatography	3.17E+01	1.36E+00	9.31E-03	1.80E-02	2.88E-03	1.88E-03	3.70E-02	6.89E-01
603	Acrolein, Acrylonitrile	Gas Chromatography	5.26E+01	2.66E+00	1.50E-02	2.68E-02	4.08E-03	2.56E-03	7.98E-02	1.07E+00
604	Phenols	FIDGC	7.07E+01	3.23E+00	2.36E-02	5.11E-02	7.26E-03	5.25E-03	1.47E-01	1.49E+00
605	Benzidines	HPLC	1.35E+02	6.39E+00	1.09E-01	2.50E-01	3.74E-02	2.75E-02	2.52E-01	2.98E+00
606	Phthalate esters	Gas Chromatography	3.13E+02	1.68E+01	3.66E-01	8.56E-01	1.28E-01	9.32E-02	5.47E-01	7.05E+00
607	Nitrosamines	Gas Chromatography	5.77E+02	3.16E+01	6.96E-01	1.63E+00	2.44E-01	1.77E-01	1.03E+00	1.30E+01
608	Organochlorine pesticides, PCBs	Gas Chromatography	5.63E+02	3.08E+01	7.02E-01	1.65E+00	2.47E-01	1.79E-01	9.84E-01	1.27E+01
608.1	Organochlorine pesticides	Gas Chromatography	1.77E+02	9.18E+00	1.96E-01	4.58E-01	6.86E-02	5.00E-02	3.04E-01	3.98E+00

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
608.2	Organochlorine pesticides	Gas Chromatography	1.81E+02	9.39E+00	1.97E-01	4.59E-01	6.87E-02	5.01E-02	3.17E-01	4.06E+00
609	Nitroaromatics, Isophorone	Gas Chromatography	2.53E+02	1.07E+01	2.03E-01	4.69E-01	6.98E-02	5.24E-02	3.63E-01	5.73E+00
610	Polynuclear aromatic hydrocarbons	HPLC, GC	5.65E+02	3.09E+01	7.05E-01	1.65E+00	2.48E-01	1.80E-01	9.87E-01	1.28E+01
611	Haloethers	Gas Chromatography	6.86E+02	3.77E+01	8.70E-01	2.04E+00	3.06E-01	2.22E-01	1.19E+00	1.55E+01
612	Chlorinated hydrocarbons	Gas Chromatography	1.77E+02	9.18E+00	1.96E-01	4.58E-01	6.86E-02	5.00E-02	3.04E-01	3.98E+00

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
613	2,3,7,8tetrachlorodibenzo-p-dioxin	GC/MS	5.98E+02	3.24E+01	7.22E-01	1.69E+00	2.53E-01	1.84E-01	1.04E+00	1.35E+01
614	Organophosphorus pesticides	Gas Chromatography	6.92E+02	3.81E+01	8.64E-01	2.03E+00	3.04E-01	2.21E-01	1.21E+00	1.56E+01
614.1	Organophosphorus pesticides	Gas Chromatography	2.61E+02	1.39E+01	2.77E-01	6.46E-01	9.64E-02	6.99E-02	4.59E-01	5.82E+00
615	Chlorinated herbicides	Gas Chromatography	2.46E+02	1.24E+01	1.97E-01	4.54E-01	6.72E-02	4.82E-02	4.36E-01	5.29E+00
617	Organochlorine pesticides, PCBs	Gas Chromatography	6.90E+02	3.79E+01	8.70E-01	2.04E+00	3.06E-01	2.22E-01	1.21E+00	1.56E+01
619	Triazine pesticides	Gas Chromatography	7.30E+02	3.93E+01	8.67E-01	2.03E+00	3.04E-01	2.21E-01	1.26E+00	1.65E+01
622	Organophosphorus pesticides	Gas Chromatography	7.81E+01	3.43E+00	2.28E-02	4.84E-02	6.80E-03	4.94E-03	1.52E-01	1.64E+00
622.1	Thiophosphate pesticides	Gas Chromatography	7.63E+01	3.36E+00	2.25E-02	4.81E-02	6.77E-03	4.95E-03	1.51E-01	1.60E+00
624	Purgeable organics	GC/MS	7.19E+01	3.57E+00	3.30E-02	6.88E-02	1.04E-02	7.01E-03	9.68E-02	1.51E+00
625	Organic compounds	GC/MS	5.76E+02	3.15E+01	7.20E-01	1.69E+00	2.53E-01	1.84E-01	1.01E+00	1.30E+01
632	Carbamate and urea pesticides	HPLC	7.42E+02	4.09E+01	9.47E-01	2.22E+00	3.33E-01	2.42E-01	1.30E+00	1.68E+01
OIA-1677-09	Cyanide	Ligand Exchange/ FIA	8.45E+01	3.07E+00	7.23E-03	8.36E-03	1.09E-03	1.16E-03	2.26E-01	1.73E+00

* The analytical methods in this table are promulgated under the Clean Water Act (CWA) section 304(h)

Table 29. Emission factors for all methods based on 3.5 quality control samples and 5 calibration curve samples with no field samples

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
120.1	Conductance	Conductivity Meter	4.41E+02	2.43E+01	5.63E-01	1.32E+00	1.98E-01	1.44E-01	7.60E-01	9.99E+00
130.1	Hardness Total	Spectrophotometer	1.02E+02	4.02E+00	1.25E-02	2.13E-02	2.67E-03	1.56E-03	1.51E-01	2.10E+00
150.2	pH	pH Meter	6.22E+00	2.05E-01	8.61E-04	1.51E-03	2.19E-04	1.39E-04	5.40E-03	1.32E-01
160.4	Residue, Volatile	Muffle Furnace	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1613BA	Chlorinated Dioxins, Furans	HRGC/HRMS	2.44E+00	1.03E-01	4.09E-04	7.88E-04	1.09E-04	7.17E-05	3.76E-03	5.26E-02
1613BS	Chlorinated Dioxins, Furans	HRGC/HRMS	2.44E+00	1.03E-01	4.09E-04	7.88E-04	1.09E-04	7.17E-05	3.76E-03	5.26E-02
1613BT	Chlorinated Dioxins, Furans	HRGC/HRMS	2.68E+00	1.13E-01	4.49E-04	8.67E-04	1.19E-04	7.89E-05	4.14E-03	5.79E-02
1624B	Organic compounds	GC/MS	2.36E+02	1.13E+01	2.12E-01	4.90E-01	7.34E-02	5.30E-02	3.45E-01	5.22E+00
1625B	Organic compounds	GC/MS	1.63E+02	8.95E+00	2.07E-01	4.85E-01	7.28E-02	5.28E-02	2.81E-01	3.68E+00
1627	Mine Drainage Quality	Column Apparatus	6.30E-01	1.32E-02	7.43E-05	1.05E-04	1.65E-05	1.02E-05	3.41E-03	9.42E-03
1631E	Mercury	CVAFS	2.10E+02	1.07E+01	1.15E-01	2.52E-01	3.72E-02	3.08E-02	5.46E-01	4.08E+00
1664A	HEM, SGT-HEM	Extraction/ Gravimetry	1.81E+02	8.93E+00	1.95E-01	4.54E-01	6.80E-02	4.96E-02	2.98E-01	3.99E+00
1664B	HEM, SGT-HEM	Extraction/ Gravimetry	5.29E+01	2.73E+00	5.50E-02	1.28E-01	1.91E-02	1.40E-02	9.40E-02	1.18E+00
180.1	Turbidity	Nephelometry	8.83E+00	3.92E-01	6.18E-03	1.42E-02	2.11E-03	1.53E-03	1.41E-02	1.91E-01
200.2 ATRA	Sample Preparation Procedure for Spectrochemical Determination of	ICP-AES	3.96E+01	3.04E+00	7.09E-03	5.05E-03	7.30E-04	1.64E-03	1.01E-01	7.33E-01

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
	Total Recoverable Elements									
200.2 STRA	Sample Preparation Procedure for Spectrochemical Determination of Total Recoverable Elements	ICP-AES	3.96E+01	3.04E+00	7.09E-03	5.05E-03	7.30E-04	1.64E-03	1.01E-01	7.33E-01
200.5	Trace Elements in Drinking Water	AVICP-AES	1.37E+02	7.36E+00	3.11E-02	4.71E-02	6.81E-03	4.92E-03	3.15E-01	2.73E+00
200.7ADA	Metals and Trace Elements in Water and Wastes	ICP-AES	8.38E+02	4.79E+01	1.04E+00	2.43E+00	3.65E-01	2.66E-01	1.56E+00	1.88E+01

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
200.7 ATRA	Metals and Trace Elements in Water and Wastes	ICP-AES	8.37E+02	4.79E+01	1.04E+00	2.43E+00	3.65E-01	2.66E-01	1.56E+00	1.88E+01
200.7 STRA	Metals and Trace Elements in Water and Wastes	ICP-AES	8.38E+02	4.79E+01	1.04E+00	2.43E+00	3.65E-01	2.66E-01	1.56E+00	1.88E+01
200.8ADA	Trace Elements in Water and Wastes	ICP-MS	5.03E+01	3.74E+00	9.13E-03	7.64E-03	1.09E-03	1.82E-03	1.29E-01	9.64E-01
200.8 ATRA	Trace Elements in Water and Wastes	ICP-MS	4.93E+01	3.70E+00	9.04E-03	7.51E-03	1.08E-03	1.81E-03	1.28E-01	9.44E-01
200.8 STRA	Trace Elements in Water and Wastes	ICP-MS	5.03E+01	3.74E+00	9.13E-03	7.65E-03	1.09E-03	1.82E-03	1.29E-01	9.64E-01
200.9	Trace Elements in Drinking Water	GFAA	4.93E+02	2.06E+01	1.98E-01	4.25E-01	6.32E-02	4.63E-02	6.71E-01	1.05E+01

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
206.5	Arsenic	AA	7.31E-01	3.09E-02	1.23E-04	2.36E-04	3.26E-05	2.15E-05	1.13E-03	1.58E-02
218.6	Hexavalent Chromium	Ion Chromatography	1.14E+02	1.83E+00	2.96E-02	5.63E-02	8.77E-03	5.86E-03	1.56E-01	1.65E+00
231.2	Gold	AA	6.17E+01	3.42E+00	7.74E-02	1.81E-01	2.72E-02	1.98E-02	1.11E-01	1.39E+00
235.2	Iridium	AA	6.17E+01	3.42E+00	7.74E-02	1.81E-01	2.72E-02	1.98E-02	1.11E-01	1.39E+00
245.1	Mercury	CVAAS	4.11E+01	3.25E+00	7.32E-03	6.61E-03	7.92E-04	4.36E-04	7.34E-02	8.57E-01
245.2	Mercury	AA	1.71E+01	9.09E-01	2.27E-03	3.98E-03	4.11E-04	2.98E-04	4.89E-02	3.37E-01
245.7	Mercury	CVAFS	3.92E+02	2.17E+01	4.90E-01	1.15E+00	1.72E-01	1.25E-01	7.03E-01	8.84E+00
252.2	Osmium	AA	6.18E+01	3.44E+00	7.74E-02	1.81E-01	2.72E-02	1.98E-02	1.11E-01	1.40E+00
253.2	Palladium	AA	6.17E+01	3.42E+00	7.74E-02	1.81E-01	2.72E-02	1.98E-02	1.11E-01	1.39E+00
255.2	Platinum	AA	6.17E+01	3.42E+00	7.74E-02	1.81E-01	2.72E-02	1.98E-02	1.11E-01	1.39E+00
265.2	Rhodium	AA	6.17E+01	3.42E+00	7.74E-02	1.81E-01	2.72E-02	1.98E-02	1.11E-01	1.39E+00
267.2	Ruthenium	AA	6.20E+01	3.42E+00	7.74E-02	1.81E-01	2.72E-02	1.98E-02	1.12E-01	1.40E+00
279.2	Thallium	AA	6.17E+01	3.42E+00	7.74E-02	1.81E-01	2.72E-02	1.98E-02	1.11E-01	1.39E+00
283.2	Titanium	AA	6.17E+01	3.42E+00	7.74E-02	1.81E-01	2.72E-02	1.98E-02	1.11E-01	1.39E+00
289.2	Zinc	AA	6.17E+01	3.42E+00	7.74E-02	1.81E-01	2.72E-02	1.98E-02	1.11E-01	1.39E+00
300	Inorganic Anions	Ion Chromatography	5.92E+01	2.28E+00	1.61E-02	3.41E-02	5.01E-03	3.92E-03	1.55E-01	1.22E+00
300.1	Inorganic Anions	Ion Chromatography	5.86E+01	2.10E+00	1.40E-02	2.87E-02	4.23E-03	2.98E-03	7.42E-02	1.24E+00
310.2	Alkalinity	Autoanalyzer	2.03E+02	9.58E+00	1.75E-01	4.05E-01	6.06E-02	4.40E-02	3.10E-01	4.47E+00
314	Perchlorate	Ion Chromatography	1.89E+02	7.34E+00	2.63E-02	4.69E-02	6.19E-03	3.51E-03	2.17E-01	3.96E+00
335.4	Cyanide	Semi-automated Colorimetry	8.50E+01	4.37E+00	2.58E-02	5.54E-02	7.49E-03	5.19E-03	2.14E-01	1.72E+00
350.1	Ammonia Nitrogen	Semi-automated Colorimetry	5.13E+01	2.31E+00	5.44E-03	8.82E-03	9.76E-04	9.06E-04	1.57E-01	1.02E+00
351.1	Kjeldahl Nitrogen	Autoanalyzer	1.52E+02	7.39E+00	1.82E-02	2.98E-02	3.00E-03	1.60E-03	4.10E-01	3.01E+00
351.2	Kjeldahl Nitrogen	Semi-automated Colorimetry	5.84E+01	3.12E+00	1.28E-02	2.61E-02	3.25E-03	2.10E-03	1.79E-01	1.13E+00

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
352.1	Nitrogen, Nitrate	Spectrophotometer	3.03E+01	1.62E+00	4.39E-03	7.28E-03	7.48E-04	3.98E-04	8.10E-02	5.95E-01
353.2	Nitrite singly	Automated Colorimetry	2.21E+01	1.00E+00	2.61E-03	6.29E-03	5.86E-04	4.70E-04	7.58E-02	4.34E-01

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
365.1	Phosphorus	Semi-automated Colorimetry	2.54E+01	1.16E+00	3.36E-03	6.16E-03	7.17E-04	5.33E-04	6.74E-02	5.11E-01
365.3	Phosphorus	Spectrophotometer	2.67E+01	1.35E+00	3.35E-03	6.07E-03	6.03E-04	3.79E-04	6.88E-02	5.35E-01
365.4	Phosphorus	Autoanalyzer	2.97E+01	1.46E+00	3.62E-03	6.36E-03	6.46E-04	4.31E-04	7.86E-02	5.96E-01
375.2	Sulfate	Automated Colorimetry	2.58E+02	1.13E+01	4.24E-02	5.82E-02	8.20E-03	4.49E-03	3.74E-01	5.25E+00
410.3	Chemical Oxygen Demand	Titration	9.41E+02	5.32E+01	1.04E+00	2.43E+00	3.61E-01	2.60E-01	2.05E+00	2.08E+01
410.4	Chemical Oxygen Demand	Semi-automated Colorimetry	2.30E+02	1.36E+01	1.00E-01	2.23E-01	3.05E-02	2.01E-02	4.97E-01	4.68E+00
420.1CE	Phenolics	#N/A	1.83E+01	9.07E-01	2.23E-03	4.01E-03	4.16E-04	3.17E-04	5.43E-02	3.62E-01
420.1DP	Phenolics	#N/A	1.83E+01	9.07E-01	2.23E-03	4.01E-03	4.16E-04	3.17E-04	5.43E-02	3.62E-01
420.4	Phenolics	Semi-automated Colorimetry	2.65E+01	1.30E+00	2.34E-02	5.43E-02	8.11E-03	5.94E-03	5.33E-02	5.80E-01
525.1	Organic Compounds in Drinking Water	GC/MS	1.78E+02	9.46E+00	2.08E-01	4.87E-01	7.29E-02	5.29E-02	2.96E-01	4.01E+00
525.2	Organic Compounds in Drinking Water	GC/MS	1.78E+02	9.46E+00	2.08E-01	4.87E-01	7.29E-02	5.29E-02	2.96E-01	4.01E+00
601	Purgeable Halocarbons	Gas Chromatography	8.46E+01	3.69E+00	5.84E-02	1.33E-01	2.00E-02	1.44E-02	1.07E-01	1.85E+00
602	Purgeable aromatics	Gas Chromatography	6.06E+01	2.95E+00	5.68E-02	1.32E-01	1.98E-02	1.43E-02	9.68E-02	1.34E+00
603	Acrolein, Acrylonitrile	Gas Chromatography	9.78E+01	4.18E+00	5.95E-02	1.35E-01	2.01E-02	1.46E-02	1.59E-01	2.10E+00
604	Phenols	FIDGC	1.90E+02	9.24E+00	1.72E-01	3.99E-01	5.97E-02	4.35E-02	3.18E-01	4.23E+00
605	Benzidines	HPLC	8.33E+01	3.14E+00	3.18E-02	6.86E-02	1.02E-02	7.71E-03	1.25E-01	1.83E+00
606	Phthalate esters	Gas Chromatography	3.20E+02	1.76E+01	3.95E-01	9.26E-01	1.39E-01	1.01E-01	5.53E-01	7.21E+00
607	Nitrosamines	Gas Chromatography	5.80E+02	3.20E+01	7.32E-01	1.72E+00	2.57E-01	1.87E-01	1.02E+00	1.31E+01
608	Organochlorine pesticides, PCBs	Gas Chromatography	5.70E+02	3.15E+01	7.31E-01	1.72E+00	2.57E-01	1.87E-01	9.89E-01	1.29E+01
608.1	Organochlorine pesticides	Gas Chromatography	1.84E+02	9.95E+00	2.25E-01	5.28E-01	7.91E-02	5.74E-02	3.09E-01	4.15E+00
608.2	Organochlorine pesticides	Gas Chromatography	1.88E+02	1.02E+01	2.26E-01	5.28E-01	7.92E-02	5.74E-02	3.23E-01	4.23E+00
609	Nitroaromatics, Isophorone	Gas Chromatography	2.58E+02	1.14E+01	2.30E-01	5.35E-01	7.97E-02	5.94E-02	3.66E-01	5.86E+00
610	Polynuclear aromatic hydrocarbons	HPLC, GC	5.89E+02	3.26E+01	7.56E-01	1.78E+00	2.66E-01	1.93E-01	1.02E+00	1.33E+01

Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
611	Haloethers	Gas Chromatography	6.93E+02	3.85E+01	8.99E-01	2.11E+00	3.16E-01	2.30E-01	1.20E+00	1.57E+01
Method/ Impact Category	Method Name	Description	Energy Demand – CED (MJ)	Global Warming – GWP ₁₀₀ (kg CO ₂ eq)	NO _x (kg NO _x)	SO _x (kg SO _x)	PM ₁₀ (kg PM)	HAPs (kg HAPs)	Water Use (m ³ H ₂ O)	Fossil Depletion – FDP (kg oil eq)
612	Chlorinated hydrocarbons	Gas Chromatography	1.84E+02	9.95E+00	2.25E-01	5.28E-01	7.91E-02	5.74E-02	3.09E-01	4.15E+00
613	2,3,7,8tetrachlorodibenzo- p- dioxin	GC/MS	6.89E+02	3.82E+01	8.83E-01	2.07E+00	3.10E-01	2.25E-01	1.20E+00	1.56E+01
614	Organophosphorus pesticides	Gas Chromatography	7.00E+02	3.88E+01	9.01E-01	2.12E+00	3.17E-01	2.30E-01	1.23E+00	1.58E+01
614.1	Organophosphorus pesticides	Gas Chromatography	2.58E+02	1.40E+01	3.10E-01	7.27E-01	1.09E-01	7.90E-02	4.49E-01	5.81E+00
615	Chlorinated herbicides	Gas Chromatography	1.95E+02	1.05E+01	2.27E-01	5.30E-01	7.93E-02	5.75E-02	3.31E-01	4.37E+00
617	Organochlorine pesticides, PCBs	Gas Chromatography	6.97E+02	3.87E+01	8.99E-01	2.11E+00	3.17E-01	2.30E-01	1.21E+00	1.58E+01
619	Triazine pesticides	Gas Chromatography	7.69E+02	4.07E+01	9.05E-01	2.12E+00	3.17E-01	2.30E-01	1.29E+00	1.74E+01
622	Organophosphorus pesticides	Gas Chromatography	1.50E+02	6.59E+00	7.42E-02	1.66E-01	2.44E-02	1.75E-02	2.31E-01	3.23E+00
622.1	Thiophosphate pesticides	Gas Chromatography	8.90E+01	3.87E+00	5.87E-02	1.34E-01	2.00E-02	1.45E-02	1.36E-01	1.93E+00
624	Purgeable organics	GC/MS	1.59E+02	8.84E+00	2.07E-01	4.85E-01	7.27E-02	5.28E-02	2.98E-01	3.59E+00
625	Organic compounds	GC/MS	6.83E+02	3.79E+01	8.82E-01	2.07E+00	3.10E-01	2.25E-01	1.19E+00	1.55E+01
632	Carbamate and urea pesticides	HPLC	6.96E+02	3.78E+01	8.70E-01	2.04E+00	3.06E-01	2.22E-01	1.18E+00	1.58E+01
OIA-1677- 09	Cyanide	Ligand Exchange/ FIA	9.95E+01	3.64E+00	8.85E-03	1.01E-02	1.32E-03	1.23E-03	2.41E-01	2.04E+00

* The analytical methods in this table are promulgated under the Clean Water Act (CWA) section 304(h)

5.0 Conclusions

5.1 Material LCI Modeling and Emission Factor Results

Material and chemical emission factors developed in this report provide a reasonable estimate for conducting site-based environmental footprint analyses that account for upstream emissions. The EmFs were derived from currently available life cycle inventory datasets developed for commercial databases, industry trade associations, and scholarly publications. The advantage of such sources is they provide datasets that have undergone more review to increase their reliability. Although datasets are suitable for current use, future work should focus on replacing EmFs based on European datasets with data more consistent with US conditions. This may require including global datasets to reflect importation of materials.

5.2 Transportation and Onsite Equipment

The vehicle and equipment emission factors constitute a significant contribution to improving the performance of SEFA. For the first time, numerous vehicle and equipment options have been modeled using a consistent approach based on emission profile simulations using EPA's MOVES model. The approach presented in this report is reproducible and will make future updates to factors much more feasible and manageable. The resulting EmFs provide adequate coverage for most vehicle and equipment options associated with remediation sites. Further enhancement of SEFA, based on these factors, can be made during future updates to the workbooks by increasing the number of factors maintained, and aggregating vehicles and equipment at finer resolutions. Uncertainty related to engine power could be reduced by further refining the range of horsepower categories and/or associated cutoff values.

5.3 Analytical Services

The results from the Method 314.0 case study showed that electricity consumption and the use of consumables were the primary drivers of environmental impacts. Inventory results from other methods indicated similar results. It is important to note that decreasing the number of consumables or electricity used during any given method may result in undesired effects that could increase the overall environmental footprint of a method. For example, a shift towards more reusable products in favor of consumable products may increase a method's overall analysis time because more time is needed to prepare reusable products for use (as opposed to consumable products, which are typically ready for use with little to no preparation). An increase in analysis time would increase the utilization rate of electricity-consuming equipment; which, may offset the environmental gains associated with a shift towards more reusable products. Certainly, all shifts in method equipment should fall within guidelines and/or protocols stated by a method's literature.

But in addition, all potential direct and indirect environmental impacts associated with shifting method equipment should be considered before large-scale changes are implemented.

There are several areas of future work that would increase the accuracy of this study's results. While the use of chemicals was not shown to be statistically significant across emission factors for the analyzed methods, each chemical's associated inventory was only cradle-to-user and did not include disposal (i.e., end-of-life) processes. Therefore, future work could focus on developing chemical disposal inventory data. Additionally, many of the wattage values used for non-consumables were based on secondary literature (e.g., user-manuals, start-up guides). The non-consumable wattage values' accuracy could be increased if they were based on primary measurements taken directly from each non-consumable. The wattage values could be further refined if they were based on active and non-active wattage utilization for each respective nonconsumable. Similarly, the consumable mass values' accuracy could be improved if they were based on primary measurements in the form of recorded masses and material associated with each measured mass.

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7.0 Appendix 1 - Hazardous Air Pollutants included in openLCA

1,1,1-trichloroethane	chlorobenzene	naphthalene
1,1,2,2-tetrachloroethane	chloroethene	nickel (II)
1,1,2-trichloroethane	chloroform	nickel and nickel
1,2,4-trichlorobenzene	chromium (III)	compounds nitrobenzene o-
1,2-dichloroethane	chromium (VI)	anisidine o-cresol o-
1,2-dichloropropane	chromium and chromium compounds	toluidine o-xylene
1,4-dichlorobenzene	cobalt (II)	PAH, polycyclic aromatic hydrocarbons
1,4-dioxane	cobalt and cobalt	PCB-1
2,4,5-trichlorophenol	compunds cobalt-60 cresol	PCB-155
2,4,6-trichlorophenol	cumene	PCB-77 (3,3',4,4'-
2,4-dinitrophenol	cyanide and cyanide compounds dibenzofuran	tetrachlorobiphenyl) p-cresol
2,4-dinitrotoluene	dibutylphthalate dichlorobenzene	pentachlorophenol phenol phosphine
2-chloro-1-phenylethanone	dichloromethane diethanolamine dimethyl	phosphorus plutonium-238
3,3'-dimethoxybenzidine	formamide dimethyl sulfate	plutonium-alpha polychlorinated
4-aminobiphenyl	dimethylphthalate dioxins (as 2,3,7,8-	biphenyls
4-methyl-2-pentanone	tetrachlorodibenzo-p-dioxin) dioxins and	propanal propylene
4-nitrophenol	furans, unspecified epichlorohydrin ethyl	oxide p-xylene
acetaldehyde	acrylate ethylbenzene ethylene glycol	radium-226
acetamide	ethylene oxide formaldehyde	radium-228 radon-
acetonitrile	hexachlorobenzene hexachloroethane	220 radon-222
acetophenone	hexane	selenium selenium
acrolein	hydrazine	(IV) styrene t-butyl
acrylic acid	hydrogen	methyl ether
acrylonitrile	chloride	tetrachloroethene
aniline	hydrogen	tetrachloromethane
antimony	fluoride	thorium-228
(III)	hydroquinone	thorium-230
antimony and antimony compounds	iodine-129	thorium-232
arsenic (V)	iodine-131	thorium-234
arsenic (III)	iodine-133	toluene
arsenic and arsenic	iodine-135	trichloroethene
compounds arsine asbestos	lead (II)	triethyl amine
benzene benzidine benzyl	lead and lead compounds	trifluralin
chloride beryllium beryllium	manganese and manganese	uranium
(II) biphenyl bis(2-	compounds mercury (II) mercury and	uranium-234
chloroethyl)ether bromoform	mercury compounds methanol methyl	uranium-235
bromomethane	methacrylate methylhydrazine	uranium-238
butadiene	monochloroethane m-xylene	uranium-alpha
cadmium		vinyl acetate
cadmium (II)		xylene
carbon disulfide		
catechol cesium-		
137 chlorine		
chloroacetic acid		

8.0 Appendix 2 - Summary of Analytical Methods

Table A1.1. Methods (i.e., analytical testing activities promulgated under the Clean Water Act (CWA) section 304(h)) included in analysis

No.	Analyte(s)	Equipment	Class	Sub Class	Sub Class
120.1	Conductance	Conductivity Meter	Spectroscopy	Conductance	Conductivity cell
130.1	Hardness Total	Spectrophotometer	Spectroscopy	Colorimetry	Complexation
150.2	pH	pH Meter	Spectroscopy	pH	NA
160.4	Residue, Volatile	Muffle Furnace	Thermal	Gravimetric	Furnace
180.1	Turbidity	Nephelometry	Spectroscopy	Turbidity	NA
200.5	Trace Elements in Drinking Water	AVICP-AES	Spectroscopy	Inductively Coupled Plasma	Spectrophotometer
200.9	Trace Elements in Drinking Water	GFAA	Spectroscopy	Atomic Adsorption	Graphite Furnace
206.5	Arsenic	AA	Spectroscopy	Atomic Adsorption	Spectrophotometer
218.6	Hexavalent Chromium	Ion Chromatography	Chromatography	Ion	Spectrophotometer
231.2	Gold	AA	Spectroscopy	Atomic Adsorption	Graphite Furnace
235.2	Iridium	AA	Spectroscopy	Atomic Adsorption	Spectrophotometer
245.1	Mercury	CVAAS	Spectroscopy	Atomic Adsorption	Spectrophotometer
245.2	Mercury	AA	Spectroscopy	Atomic Adsorption	Spectrophotometer
245.7	Mercury	CVAFS	Spectroscopy	Atomic Fluorescence	Spectrophotometer
252.2	Osmium	AA	Spectroscopy	Atomic Adsorption	Spectrophotometer
253.2	Palladium	AA	Spectroscopy	Atomic Adsorption	Spectrophotometer
255.2	Platinum	AA	Spectroscopy	Atomic Adsorption	Spectrophotometer
265.2	Rhodium	AA	Spectroscopy	Atomic Adsorption	Spectrophotometer
267.2	Ruthenium	AA	Spectroscopy	Atomic Adsorption	Spectrophotometer
279.2	Thallium	AA	Spectroscopy	Atomic Adsorption	Spectrophotometer
283.2	Titanium	AA	Spectroscopy	Atomic Adsorption	Spectrophotometer

No.	Analyte(s)	Equipment	Class	Sub Class	Sub Class
289.2	Zinc	AA	Spectroscopy	Atomic Adsorption	Spectrophotometer
300	Inorganic Anions	Ion Chromatography	Chromatography	Ion	Conductivity cell
300.1	Inorganic Anions	Ion	Chroma-	Ion	Conductivity cell

		Chromatography	tography		
310.2	Alkalinity	Autoanalyzer	Spectroscopy	Colorimetry	Visual
314	Perchlorate	Ion Chromatography	Chromatography	Ion	Conductivity cell
335.4	Cyanide	Semi-automated Colorimetry	Spectroscopy	Colorimetry	Colorimeter
350.1	Ammonia Nitrogen	Semi-automated Colorimetry	Spectroscopy	Colorimetry	Colorimeter
351.1	Kjeldahl Nitrogen	Autoanalyzer	Spectroscopy	Colorimetry	Colorimeter
351.2	Kjeldahl Nitrogen	Semi-automated Colorimetry	Spectroscopy	Colorimetry	Colorimeter
352.1	Nitrogen, Nitrate	Spectrophotometer	Spectroscopy	Colorimetry	Spectrophotometer
353.2	Nitrite singly	Automated Colorimetry	Spectroscopy	Colorimetry	Colorimeter
365.1	Phosphorus	Semi-automated Colorimetry	Spectroscopy	Colorimetry	Colorimeter
365.3	Phosphorus	Spectrophotometer	Spectroscopy	Colorimetry	Spectrophotometer
365.4	Phosphorus	Autoanalyzer	Thermal	Colorimetry	Autoanalyzer
375.2	Sulfate	Automated Colorimetry	Spectroscopy	Colorimetry	Colorimeter
410.3	Chemical Oxygen Demand	Titration	Spectroscopy	Colorimetry	Titration
410.4	Chemical Oxygen Demand	Semi-automated Colorimetry	Spectroscopy	Colorimetry	Colorimeter
420.1	Phenolics	Spectrophotometer	Spectroscopy	Distillation	Spectrophotometer
420.4	Phenolics	Semi-automated Colorimetry	Spectroscopy	Colorimetry	Colorimeter
525.1	Organic Compounds in Drinking Water	GC/MS	Chromatography	Gas	Mass Spectroscopy
525.2	Organic Compounds in Drinking Water	GC/MS	Chromatography	Gas	Mass Spectroscopy
601	Purgeable Halocarbons	Gas Chromatography	Chromatography	Gas	Electron Capture or Microcoulometric Detector

		Chromatography	tography		
602	Purgeable aromatics	Gas Chromatography	Chromatography	Gas	Photoionization detector
603	Acrolein, Acrylonitrile	Gas Chromatography	Chromatography	Gas	Flame Ionization Detector
604	Phenols	FIDGC	Chromatography	Gas	Flame Ionization Detector
605	Benzidines	HPLC	Chromatography	Liquid	Electro-chemical Detector
606	Phthalate esters	Gas Chromatography	Chromatography	Gas	Electron Capture Detector
607	Nitrosamines	Gas Chromatography	Chromatography	Gas	Nitrogen Phosphorus, Reductive Hall, or

					Thermal Energy Analyzer
608	Organochlorine pesticides, PCBs	Gas Chromatography	Chromatography	Gas	Electron Capture Detector
608.1	Organochlorine pesticides	Gas Chromatography	Chromatography	Gas	Electron Capture Detector
608.2	Organochlorine pesticides	Gas Chromatography	Chromatography	Gas	Electron Capture Detector
609	Nitroaromatics, Isophorone	Gas Chromatography	Chromatography	Gas	Flame Ionization Detector and Electron Capture Detector
610	Polynuclear aromatic hydrocarbons	HPLC, GC	Chromatography	Liquid	Flame Ionization Detector
611	Haloethers	Gas Chromatography	Chromatography	Gas	Halide Specific: Electrolytic Conductivity or Microcoulometric Detector
612	Chlorinated hydrocarbons	Gas Chromatography	Chromatography	Gas	Electron Capture Detector
613	2,3,7,8tetrachlorodibenzop-dioxin	GC/MS	Chromatography	Gas	Mass Spectroscopy
614	Organophosphorus pesticides	Gas Chromatography	Chromatography	Gas	Flame Photometric Detector or Thermionic Bead Detector
614.1	Organophosphorus pesticides	Gas Chromatography	Chromatography	Gas	Nitrogenphosphorus Detector

					Thermal Energy Analyzer
615	Chlorinated herbicides	Gas Chromatography	Chromatography	Gas	Electron Capture Detector
617	Organochlorine pesticides, PCBs	Gas Chromatography	Chromatography	Gas	Electron Capture Detector
619	Triazine pesticides	Gas Chromatography	Chromatography	Gas	Thermionic Bead Detector (Nitrogen Mode)
622	Organophosphorus pesticides	Gas Chromatography	Chromatography	Gas	Flame Photometric or Thermionic Bead Detector (Phosphorus Mode)
622.1	Thiophosphate pesticides	Gas Chromatography	Chromatography	Gas	Alkali flame Detector
624	Purgeable organics	GC/MS	Chromatography	Gas	Mass Spectroscopy
625	Organic compounds	GC/MS	Chromatography	Gas	Mass Spectroscopy
632	Carbamate and urea pesticides	HPLC	Chromatography	Liquid	Ultraviolet - Visible

					Spectroscopy
1627	Mine Drainage Quality	Column Apparatus	Spectroscopy	Multiple	NA
1613BA	Chlorinated Dioxins, Furans	HRGC/HRMS	Chromatography	Gas	Mass Spectroscopy
1613BS	Chlorinated Dioxins, Furans	HRGC/HRMS	Chromatography	Gas	Mass Spectroscopy
1613BT	Chlorinated Dioxins, Furans	HRGC/HRMS	Chromatography	Gas	Mass Spectroscopy
1624B	Organic compounds	GC/MS	Chromatography	Gas	Mass Spectroscopy
1625B	Organic compounds	GC/MS	Chromatography	Gas	Mass Spectroscopy
1631E	Mercury	CVAFS	Spectroscopy	Atomic Fluorescence	Spectrophotometer
1664A	HEM, SGT-HEM	Extraction/ Gravimetry	Extraction	Gravimetric	NA
1664B	HEM, SGT-HEM	Extraction/ Gravimetry	Extraction	Gravimetric	NA

					Spectroscopy
200.2 ATRA	Sample Preparation Procedure for Spectrochemical Determination of Total Recoverable Elements	ICP-AES	Spectroscopy	Inductively Coupled Plasma	Spectrophotometer
200.2 STRA	Sample Preparation Procedure for Spectrochemical Determination of Total Recoverable Elements	ICP-AES	Spectroscopy	Inductively Coupled Plasma	Spectrophotometer
200.7 ADA	Metals and Trace Elements in Water and Wastes	ICP-AES	Spectroscopy	Inductively Coupled Plasma	Spectrophotometer
200.7 ATRA	Metals and Trace Elements in Water and Wastes	ICP-AES	Spectroscopy	Inductively Coupled Plasma	Spectrophotometer
200.7 STRA	Metals and Trace Elements in Water and Wastes	ICP-AES	Spectroscopy	Inductively Coupled Plasma	Spectrophotometer
200.8 ADA	Trace Elements in Water and Wastes	ICP-MS	Spectroscopy	Inductively Coupled Plasma	Spectrophotometer
200.8 ATRA	Trace Elements in Water and Wastes	ICP-MS	Spectroscopy	Inductively Coupled Plasma	Spectrophotometer
200.8 STRA	Trace Elements in Water and Wastes	ICP-MS	Spectroscopy	Inductively Coupled Plasma	Spectrophotometer
OIA- 1677-09	Cyanide	Ligand Exchange/FIA	Spectroscopy	Electrochemical	Amperometric

9.0 Appendix 3 - Summary of Chemicals

Table A2.1. List of chemicals utilized as flows

Chemical Name (# to J)	Chemical Name (K to Z)
0-(2,3,5,6-Pentafluorobenzyl)-hydroxylamine hydrochloride (PFBHA)	L-ascorbic acid
1,2-Dibromopropane	Lead
1,2-Dimethyl-3-nitrobenzene	Lead (II) nitrate
1,3-Dimethyl-2-nitrobenzene	Liquid-solid extraction (LSE) cartridges
1,5-Diphenylcarbazine	Lithium
1-10-(ortho) phenanthroline monohydrate	Lithium carbonate
18-crown-6-ether (1,4,7,10,13,16-Hexaoxacyclooctadecane)	Magnesium
1-Heptanesulfonic acid	Magnesium chloride
1-Hexanesulfonic acid	Magnesium chloride hexahydrate
2,3,4,5-Tetrachlorophenol	Manganese
2,4,5-T	Magnesium nitrate
2,4,5-TP	Mercuric chloride
2,4,5-Trifluoroacetophenone	Mercuric oxide
2,4,6-Tribromophenol	Mercuric sulfate
2,4-D	Mercury
2,4-DB	Mercury (II) cyanide
2,4-Dimethylphenol-3,5,6-d	N/A
2,6-Diphenylene oxide polymer	Mercury (II) oxide
2-Chlorophenol-3,4,5,6-d	Methanol
2-propanol	Methyl iodide
3,5-Dichlorobenzoic acid	Methyl mercury chloride
4-Aminoantipyrine	Methyl orange
4-Nitrophenol	Methyl silicone
5-[4-(Dimethylamino)benzylidene]rhodanine	Methyl tert-butyl ether
5-Hydroxydicamba	Methylene chloride
Acenaphthene	Methylthymol blue
Acetate buffer	MgEDTA
Acetic acid	Molybdenum
Acetone	Molybdenum trioxide
Acetonitrile	Monomagnesium ethylenediamine-tetraacetate
Acid alumina	Monuron
Acid silica gel	N-1-naphthylethylenediamine dihydrochloride
Acifluorfen	n-Hexane

Chemical Name (# to J)	Chemical Name (K to Z)
Activated carbon	Nickel
Alkaline phenol	Nickel (II) cyanide
Alumina	Nickel potassium cyanide

Aluminum	Nitrate
Aminoantipyrine	Nitric acid
Ammonium chloride	Nitrite
Ammonium fluorosilicate	Nitrogen
Ammonium hydroxide	Nonane
Ammonium iron (II) sulfate	Orthophosphoric acid
Ammonium molybdate	Ortho-xylene
Ammonium nitrate	Palladium
Ammonium persulfate	Paraquat dichloride
Ammonium phosphate monobasic	Pentachlorophenol
Ammonium sulfate	Pentafluorobenzyl bromide (α Bromopentafluorotoluene)
Ammonium titanyl oxalate monohydrate	Pentane
Antimony	Perchlorate stock standard
Antimony potassium tartrate	Petroleum ether
Argon	Phenanthrene
Argon gas	Phenanthroline ferrous
Arsenic	Phenol
Arsenic trioxide	Phenolphthalein
Arsenite	Phosphate
Ascorbic acid	Phosphoric acid
Barbituric acid	Phosphorus
Barium	Picloram
Barium carbonate	Potassium
Barium chloride	Potassium acid phthalate
Barium chloride dihydrate	Potassium bromate
Basic alumina	Potassium bromide
Bentazon	Potassium carbonate
Benzene	Potassium chloride
Beryllium	Potassium cyanide
Beryllium sulfate	Potassium dichromate

Aluminum	Nitrate
Beryllium sulfate tetrahydrate	Potassium ferricyanide
Beryllium sulfite tetrahydrate	Potassium hydrogen phthalate
Bismuth	Potassium hydroxide
Bismuth (III) oxide	Potassium nitrite
Bismuth nitrate pentahydrate	Potassium nitrate
Boiling chips	Potassium permanganate
Borate	Potassium persulfate
Boric acid	Potassium phosphate
Boron	Potassium silicate
Brij-35	Potassium sulfate

Bromate	Pyridine
Bromide	Quartz sand
Bromine monochloride	Scandium
Brucine sulfanilic acid	Scandium oxide
Brucine sulfate	Selenium
Cadmium	Selenium dioxide
Calcium	Silica
Calcium carbonate	Silica gel
Calmagite	Silicic acid
Carbazole	Silicon carbide
Carbitol	Silver
Carbon dioxide (gas)	Silver nitrate
Carbopak C	Silver sulfate
Cerium	Sodium
Cerium (IV) oxide	Sodium acetate
Cetyl trimethyl ammonium bromide	Sodium acetate trihydrate
Chloramben	Sodium arsenite
Chloramine-T	Sodium bisulfite
Chlorate	Sodium bicarbonate
Chloride	Sodium bromate
Chlorite	Sodium bromide
Chloroform	Sodium carbonate
Chromium	CJTOFF: Sodium chlorate

Bromate	Pyridine
Chromium trioxide	Sodium chloride
Chrysene	Sodium chlorite
Cobalt	Sodium chromate tetrahydrate
Coconut charcoal	Sodium fluoride
Copper	Sodium chloride-hydroxylammonium chloride
Copper (II) sulfate pentahydrate	Sodium dihydrogenphosphate
Copper cadmium	Sodium hydroxide
Copper powder	Sodium hypochlorite
Copper sulfate	Sodium nitrate
Cupric sulfate	Sodium nitrite
Cyanide	Sodium nitroprusside
Cyclohexane	Sodium perchlorate
Dacthal acid metabolites	Sodium phenolate
Dalapon	Sodium phosphate
Decafluorotriphenylphosphine	Sodium potassium tartrate
Deionized water; laboratory grade	Sodium salicylate
DFTPP	Sodium sulfate

Diazald	Sodium sulfite
Diazolidinyl urea	Sodium tetraborate decahydrate
Dibromooctafluorobiphenyl	Sodium thiosulfate
Dicamba	Sodium tribasic phosphate
Dichloroacetate	Stannous chloride
Dichlorophenylacetic acid	Stannous sulfate
Dichlorprop	Stearic acid
Diethylamine	Strontium
Diflubenzuron	Strontium carbonate
Dinoseb	Sulfamic acid
Dipropylene glycol monomethyl ether	Sulfanilamide
Diquat dibromide	Sulfanilic acid
Disodium ethylenediamine tetraacetate	Sulfate
Dry ice	Sulfuric acid
Ethanol	Sulfuric acid-mercuric sulfate-potassium sulfate
Ethyl acetate	Tartaric acid

Diazald	Sodium sulfite
Ethyl ether	Terbium
Ethylenediamine	Terbium (III,IV) oxide
Ethylenediamine tetraacetate	Tetrabutylammonium hydroxide
Ethylenediaminetetraacetic acid	Tetradecane
Ferrous ammonium sulfate	Tetrasodium EDTA
Ferrous iron	Thallium
Florisil	Thallium (I) nitrate
Fluoride	Thidiazuron
Glass wool	Thorium
Gold	Thorium nitrate hydrate
Helium gas	Tin
Hexadecane	Tin (II) chloride
Hexamethylenetetramine	Titanium
Hexane	Toluene
Hydrazine sulfate	Triphenylphosphate
Hydrochloric acid	Tris(hydroxymethyl)aminomethane
Hydrogen peroxide	Tris(hydroxymethyl)aminomethanehydrochloride
Hydroxylamine	Trisodium phosphate decahydrate
Hydroxylamine hydrochloride	Uranium
Hydroxylamine sulfate	Uranyl nitrate hexahydrate
Indium	Vanadium
Iron	White quartz sand
Iron (II) sulfate heptahydrate	Yttrium
Isooctane	Yttrium (III) oxide
Isopropyl alcohol	Zinc

10.0 Appendix 4 - Summary of Consumables

Table A3.1. Life cycle inventory for consumables. The term “CUTOFF” signifies flows that are bridged from non-EPA life cycle inventory databases (e.g., ecoinvent v2.2). The “CUTOFF” term is used to standardize naming conventions for different life cycle inventory databases.

Flow Name	NAICS Category	Location
CUTOFF: Laboratory paper	322121 Paper (except Newsprint) Mills	US
CUTOFF: Hydraulic injection forming; highdensity polypropylene	325211 Plastics Material and Resin Manufacturing	US
CUTOFF: Hydraulic injection forming; polystyrene	325211 Plastics Material and Resin Manufacturing	US
CUTOFF: Low-density polyethylene; at plant	325211 Plastics Material and Resin Manufacturing	US
CUTOFF: Plastic shaping; injection molding	325211 Plastics Material and Resin Manufacturing	US
CUTOFF: Polybutadiene; at plant	325211 Plastics Material and Resin Manufacturing	US
CUTOFF: Polycarbonate; at plant	325211 Plastics Material and Resin Manufacturing	US
CUTOFF: Polypropylene; at plant	325211 Plastics Material and Resin Manufacturing	US
CUTOFF: Polystyrene at plant	325211 Plastics Material and Resin Manufacturing	US
CUTOFF: Laboratory glass	327212 Other Pressed and Blown Glass and Glassware Manufacturing	US
CUTOFF: Nylon	327212 Other Pressed and Blown Glass and Glassware Manufacturing	US
CUTOFF: Air transport; freight	481112 Scheduled Freight Air Transportation	US
CUTOFF: Truck transport; freight	484121 General Freight Trucking, LongDistance, Truckload	US
CUTOFF: Disposal; inert material; 0% water; to sanitary landfill	562212 Solid Waste Landfill	US
CUTOFF: Disposal; plastics; mixture; 0% water; to sanitary landfill	562212 Solid Waste Landfill	US
CUTOFF: Disposal; polyethylene; 0% water; to sanitary landfill	562212 Solid Waste Landfill	US
CUTOFF: Disposal; polypropylene; 0% water; to sanitary landfill	562212 Solid Waste Landfill	US
CUTOFF: Disposal; polystyrene; 0% water; to sanitary landfill	562212 Solid Waste Landfill	US

Table A3.2. Primary and secondary references for consumables

Consumable	Name/Reference	Brand/Description	Mass (grams)
Boiling chip; alumina; at user	Microporous Carbon Boiling Chips	Sigma Aldrich, Ec Number 231-153-3	227
Centrifuge tube with screw cap; 15 mL; polypropylene; at user	Falcon 15 mL Conical Centrifuge Tubes	Fisher Scientific, Manufacturer Corning Inc. 352196 Polypropylene, Closure Type: Dome-Seal; Screw Cap; Threaded	14.37
Centrifuge tube with screw cap; 50 mL; polypropylene; at user	50mL Pp Centrifuge Tubes	Corning, Conical Bottom With Centristar™ Cap, Bulk Packed, Sterile, 25/Sleeve, Average (Lab)	13.26
Culture tube; 16 × 100 mm; Teflon-lined screw cap; glass; at user	Glass Culture Tube, 16Mm Diameter X 100Mm Length, 10mL	Globe Scientific 1512 Borosilicate Glass Culture Tube, 16Mm Diameter X 100Mm Length, 10mL	11.34
Digestion tube; glass; at user	Straight Digestion Tubes	Labconco, Straight Digestion Tubes, 250mL (Packet of 25)	0.29
Digester tube; glass; at user	Straight Digestion Tubes	Labconco, Straight Digestion Tubes, 250mL (Packet of 25)	0.29
Extraction thimble; cellulose; at user	Extraction Thimble Single Thickness, 50Mm Length X 10Mm Width	Whatman 2800-105 Premium Cellulose Extraction Thimble Single Thickness, 50Mm Length X 10Mm Width (Pack of 25)	1.81
Filter paper; 0.45 µm; cellulose; at user	Qualitative Filter Paper	Filter Paper, Pore 0.45Um, Dia 4.7Cm	0.91
Glass wool; borosilicate glass; at user	Glass Wool	Pyrex™ Glass Wool; 8 Micron Fiber Diameter	0.68
Gloves; polybutadiene; extended cuff and extra resistance; at user	Nitrile Gloves - The Versatile And Cost-Effective Solution For Hand Protection	Medisafe Technologies, Extended Cuff, Extra Resistance, Nit-Ch-95	9.50
Lead acetate test strip; cellulose; at user	Lead Acetate Test Paper	Precision Laboratories Lead Acetate Test Paper	0.09
Micro beaker; 20 mL polypropylene; at user	5100-2 Beaker Graduated Plastic Pp 100 mL	Sciencelabsupplies, Beaker Graduated Plastic Catalog # 5100-2-001	22.68
Micro beaker; 100mL; polypropylene; at user	5100-2 Beaker Graduated Plastic Pp 100 mL	Sciencelabsupplies, Beaker Graduated Plastic Catalog # 5100-2-001	113.40
Particulate filter; polycarbonate; at user	Name: Particulate Filter; Polycarbonate; At User	Description: Particulate Filter; Polycarbonate; At User	0.91
pH paper; at user	Phydriion Insta-Chek 0-13 Jumbo	Microessentiallab, Zoro #: G4223615 Mfr #: Jr113 (Lab)	38

Consumable	Name/Reference	Brand/Description	Mass (grams)
Pipette tip; 0.025 mL; lowdensity polyethylene; at user	Transfer Pipets, Disposable Polyethylene	Fisherbrand, Fisher Scientific, Cat No. 13-711-5Am, Average of 3 Samples of The 5mL Tips But Were Extrapolated (Lab)	0.03
Pipette tip; 0.125 mL; lowdensity polyethylene; at user	Transfer Pipets, Disposable Polyethylene	Fisherbrand, Fisher Scientific, Cat No. 13-711-5Am, Average of 3 Samples of The 5mL Tips	0.16

		But Were Extrapolated (Lab)	
Pipette tip; 0.05 mL; lowdensity polyethylene; at user	Transfer Pipets, Disposable Polyethylene	Fisherbrand, Fisher Scientific, Cat No. 13-711-5Am, Average of 3 Samples of The 5mL Tips But Were Extrapolated (Lab)	0.06
Pipette tip; 1 mL; low-density polyethylene; at user	Transfer Pipets, Disposable Polyethylene	Fisherbrand, Fisher Scientific, Cat No. 13-711-5Am, Average of 3 Samples of The 5mL Tips But Were Extrapolated (Lab)	1.27
Pipette tip; 5 mL; low-density polyethylene; at user	Sigma Aldrich Eppendorf Pipet Tip	Lab	1.80
Pipette tip; 10 mL; low-density polyethylene; at user	Disposable Polypropylene Macrotip 5mL Capacity	Wheaton Lot No 710666, Took Average of Three Samples And Extrapolated (Lab)	4.73
Pipette tip; 20 mL; low-density polyethylene; at user	Disposable Polypropylene Macrotip 5mL Capacity	Wheaton Lot No 710666, Took Average of Three Samples And Extrapolated (Lab)	9.46
Pipette tip; 25 mL; low-density polyethylene; at user	Disposable Polypropylene Macrotip 5mL Capacity	Wheaton Lot No 710666, Took Average of Three Samples And Extrapolated (Lab)	11.83
Sample bottle with cap; at user	20 mL Amber Vial	Wheaton, Blk Phenolic -Rubber Liner	19.40
Sample bottle; 100 mL; FEP; at user	20 mL Amber Vial	Wheaton, Blk Phenolic -Rubber Liner	97
Sample bottle; 125 mL; FEP; at user	20 mL Amber Vial	Wheaton, Blk Phenolic -Rubber Liner	121.25
Sample bottle; 1 L; FEP; at user	20 mL Amber Vial	Wheaton, Blk Phenolic -Rubber Liner	970
Sample bottle with lid; 20 mL; glass; at user	20 mL Amber Vial	Wheaton, Blk Phenolic -Rubber Liner	19.40
Sample bottle with lid; 25 mL; glass; at user	20 mL Amber Vial	Wheaton, Blk Phenolic -Rubber Liner	24.25
Sample bottle with lid; 500 mL; glass; at user	20 mL Amber Vial	Wheaton, Blk Phenolic -Rubber Liner	485
Sample bottle with lid; 1000 mL; glass; at user	20 mL Amber Vial	Wheaton, Blk Phenolic -Rubber Liner	970

		But Were Extrapolated (Lab)	
Sample bottle with lid; 500 mL; glass amber; at user	20 mL Amber Vial	Wheaton, Blk Phenolic -Rubber Liner	485
Sample bottle with lid; 1000 mL; glass amber; at user	20 mL Amber Vial	Wheaton, Blk Phenolic -Rubber Liner	970
Sample bottle with cap; 500 mL; polyethylene; at user	20 mL Amber Vial	Wheaton, Blk Phenolic -Rubber Liner	485
Sample bottle; 100 mL; polypropylene; at user	2 oz./60mL Wide Mouth Economy Bottle W/28Mm Cap	Nalgene, #69058, Extrapolated To 100mL	24.70
Sample bottle; 250 mL; polypropylene; at user	500 mL, Polypropylene Bottle	Fisherbrand, Fisher Scientific, Cas-7732-18-5, Average of 3, Extrapolated From The 500mL (Lab)	32.20
Sample bottle; 500 mL; polypropylene; at user	500 mL, Polypropylene Bottle	Fisherbrand, Fisher Scientific, Cas-7732-18-5 (Lab)	64
Sieve; 5-mesh; polypropylene;	Nylon Mesh Strainer	Hic Nylon Mesh Strainer, 7-Inch	45.36

at user			
Syringe with luer lock; 20mL; polypropylene; at user	Biomaterials, Wong, J. Y. and J. D. Bronzino (2007). Biomaterials. Boca Raton, FL, CRC Press. 2., Page 3-9 and Page 2	N/A	19
Syringe; 2 mL; polypropylene; at user	Biomaterials, Wong, J. Y. and J. D. Bronzino (2007). Biomaterials. Boca Raton, FL, CRC Press. 2., Page 3-9 and Page 3	N/A	2.50
Syringe; 0.025 mL; polypropylene; at user	Biomaterials, Wong, J. Y. and J. D. Bronzino (2007). Biomaterials. Boca Raton, FL, CRC Press. 2., Page 3-9 and Page 4	N/A	0.03
Syringe; 0.010 mL; polypropylene; at user	Biomaterials, Wong, J. Y. and J. D. Bronzino (2007). Biomaterials. Boca Raton, FL, CRC Press. 2., Page 3-9 and Page 5	N/A	0.01
Syringe; 5 mL; polypropylene; at user	Biomaterials, Wong, J. Y. and J. D. Bronzino (2007). Biomaterials. Boca Raton, FL, CRC Press. 2., Page 3-9 and Page 6	N/A	6.25

at user			
Syringe; 10 mL; polypropylene; at user	Biomaterials, Wong, J. Y. and J. D. Bronzino (2007). Biomaterials. Boca Raton, FL, CRC Press. 2., Page 3-9 and Page 7	N/A	12.50
Syringe; 25 mL; polypropylene; at user	Biomaterials, Wong, J. Y. and J. D. Bronzino (2007). Biomaterials. Boca Raton, FL, CRC Press. 2., Page 3-9 and Page 8	N/A	31.25
Syringe filter; nylon; at user	Syringe Filters	Seoh Syringe Filters Nylon 25Mm 0.2Um 50Pack	9.07
Syringe valve; polycarbonate; at user	Double Check Valve	Value Plastics Dcv116-001 Double Check Valve, Luer X Syringe Connection, Polycarbonate	22.68
Vial with cap; 1 mL; polypropylene; at user	Extrapolated from 10mL Vial with Cap	N/A	0.97
Vial with cap; 5 mL; polypropylene; at user	Extrapolated from 10mL Vial with Cap	N/A	4.86
Vial with cap; 10 mL; polypropylene; at user	10 mL Vial with Cap	Qorpak	9.72
Vial with cap; 15 mL; polypropylene; at user	Extrapolated from 10mL Vial with Cap	N/A	14.58
Vial with cap; 25 mL; polypropylene; at user	Extrapolated from 10mL Vial with Cap	N/A	24.30
Vial with cap; 40 mL; amber VOA; at user	Extrapolated from 10mL Vial with Cap	N/A	38.88
Vial with cap; 50 mL; amber VOA; at user	Extrapolated from 10mL Vial with Cap	N/A	48.60
Weight boat; medium; metal; at user	Aluminum Weighing Dish	Electron Microscopy Sciences, Tall Dish Measures: 4.2oz, 215/16" Dia X 17/8" Deep (75Mm X 32Mmdeep)	119
Weigh boat; large; polystyrene; at user	Dyn-A-Dish Virgin Polystyrene Weigh Boat	Large 5 1/2" X 5 1/2" X 7/8" #06008 (2 Packs of 500 Per Case)	5
Weigh boat; medium; polystyrene; at user	Dyn-A-Dish Virgin Polystyrene Weigh Boat	Medium 3 5/16" X 3 15/16" X 3/4" #55008 (4 Packs of 500 Per Case)	1.80
Weigh boat; small; polystyrene; at user	Dyn-A-Dish Virgin Polystyrene Weigh Boat	Small 1 3/4" X 1 3/4" X 3/8" #05008 (12 Packs of 500 Per Case)	0.50

11.0 Appendix 5 - Summary of Non-Consumables

Table A4.1. Secondary references for electricity consumption of non-consumables

Non-Consumable Flow	Name	Description	Wattage
Adsorber; at user; one hour of use	DC Power/Energy Absorber Test System (Sponge)	Ametek programmable power, absorber	28,800
Air blower; at user; one hour of use	Basic 47 Laboratory Hood	Labconco, benchtop, #2247300	782
Air pump; at user; one hour of use	Welch WOB-L Pump	The Lab Depot Inc., Laboratory Vacuum Pump, Model 2511B01	250
Analytical balance; 0.1 mg capability; at user; one hour of use	ED124S	ED124S Analytical Balance	16
Argon gas regulator; at user; one hour of use	Prodigy7 Series ICP Spectrometer	Teledyne Leeman Labs, Part #150-00401	7,350
Aspirator vacuum system; at user; one hour of use	LS2 Power Aspirator	M.D. Resource, LS2	14,400
Atomic absorption cold vapor system; at user; one hour of use	Flow Injection Mercury System	FIMS 100/400 Flow Injection Mercury Systems	300
Atomic absorption spectrophotometer; at user; one hour of use	FLAME Atomic Absorption Spectrometer	Buck Scientific, 210VGP	1,650
Autoclave; at user; one hour of use	Autoclave: Sterilizer, BRDG, Primus, Clinical	Medical Technologies Company, Model A, SN 17413	13,936
Automated continuous flow analysis equipment; at user; one hour of use	Automated Mercury Analyzer	Automated Mercury Analyzer AULA-254 Gold	120
Automated gel permeation chromatograph; at user; one hour of use	Gel Permeation Chromatography	Alibaba, Brand name Friend, Model FDS-0401	8,000
Block digester; at user; one hour of use	AIM600 Block Digestion System	Aiscientific, AIM600	500
Centrifuge; at user; one hour of use	Centrifuges Table-top	Sustainability.ucsc.edu	14,000
Cold vapor atomic fluorescence spectrometer (CVAFS); at user; one hour of use	Automated Methyl Mercury Analysis System	Tekran - Model 2700 - Automated Methyl Mercury Analysis System	1,625
Colorimeter; at user; one hour of use	ProMetric Imaging Photometers and Colorimeters	SphereOptics, Model IC-PMG2	1,400
Column oven and detector; at user; one hour of use	PowerPac HC	Bio-rad	2,400
Computer; with data acquisition system; at user; one hour of use	Average computer energy usage	Griffith University	3
Computer-controlled emission spectrometer; at user; one hour of use	DFS-500 Emission Spectrometer	OkB-spectr	350

Non-Consumable Flow	Name	Description	Wattage
Conductivity bridge; at user; one hour of use	Conductance Bridge	Yellow Springs Instrument, Model 31A	100
Conductivity cell; at user; one	Optisens Cond 1200	SENSOFIT IMM 1000 for	12,000

hour of use		OPTISENS COND	
Desorber; at user; one hour of use	Unity Thermal Desorber	Agilent	4,000
Desiccator; at user; one hour of use	Electrosurgical generator	Bovie Aaron 950 Electrosurgical Generator	60
Detector; at user; one hour of use	MSQ Plus Mass Detector	ThermoFisher	50,000
Drying oven; at user; one hour of use	Gas Fired Oven	Earthstone Wood-Fire Ovens, Model PA	300
Dual-trap Hg preconcentrating system; at user; one hour of use	Portable Mercury Analyzer	Ohio Lumex, RA-82 "Prospector"	50
Electrochemical detector; at user; one hour of use	UltiMate 3000 ECD-3000RS Electrochemical Detector	Thermo Scientific, Dionex, UHPLC compatibility	1,500
Freezer; at user; one hour of use	Laboratory freezer	General Laboratory Refrigerators, Freezers, and Refrigerator/Freezer Combination Units	177
Gas chromatograph; at user; one hour of use	Agilent 3000 series Gas Chromatograph	Model G2801A, G2803A	700
Gas chromatograph/mass spectrometer/data system; at user; one hour of use	Agilent 3000 series Gas Chromatograph	Model G2801A, G2803A	2,600
Graphite furnace atomic absorbance spectrophotometer; at user; one hour of use	Atomic Absorption Spectrophotometer System	SavantAA Zeeman Atomic Absorption Spectrophotometer System	3,600
Gravity convection drying oven; at user; one hour of use	Gravity Convection Ovens, Basic	VWR, 32L	5,020
Heat lamp; at user; one hour of use	Proper Infrared Heat Lamp Use	University of Missouri Extension	2,500
Heating bath; at user; one hour of use	Thermo Scientific AC200-S45, 30-41L Heated Bath, Amb +13 to 200C	Cole-Parmer, circulator	12,000
Heating block; at user; one hour of use	2" Resistive Substrate Heater	MeiVac	450
Heating mantle; at user; one hour of use	Glas-Col Flexible fabric heating mantle	Cole-Parmer, 500 ml	2,700
High performance liquid chromatograph (HPLC); at user; one hour of use	Agilent 1100 Series HPLC Value System	Model G1362A	320
Hot plate; at user; one hour of use	Hot Plate	THD Electronics	1,850

hour of use		OPTISENS COND	
Hot water bath; at user; one hour of use	Hot Water Bath	Dubnoff Reciprocal Shaking Baths	1,000
Inductively coupled plasma emission spectrometer; at user; one hour of use	iCAP™ 7200 ICP-OES Analyzer	ThermoFisher Scientific, model Duo	13,000
Integrator; at user; one hour of use	8-pin DIN Integrator	Liebert, SNMP Communications for Integrated Products	1,440
Ion chromatograph; Dionex ICS-5000; at user; one hour of use	Modular High-Pressure Ion Chromatography System	Dionex ICS-5000 Ion Chromatography System	265

Meat grinder; at user; one hour of use	Meat grinder	Knife Mill GRINDOMIX GM 200	900
Mechanical shaker; at user; one hour of use	Lab Rotators and Low Cost Orbital Shakers	Model 2309-ICE	50
Mechanical stirrer; at user; one hour of use	EUROSTAR 60 digital	IKA	1,760
Muffle furnace; at user; one hour of use	Vulcan Muffle Furnace	Neytech Model 9493308, 550 cu in, 3-stage programmable	2,400
Multichannel pump; at user; one hour of use	Peristaltic Pump Module	PendoTECH	480
Oven; at user; one hour of use	7890 Series Agilent	Americas 120 standard single phase	2,256
Overhead fume hood; at user; one hour of use	Overhead Fume Hood	HI9P Model FTM Technologies	3,200
Panel immersion heater; at user; one hour of use	Immersion heater, long rod, 20" L heated area	Cole-Parmer	11,000
Peristaltic pump; at user; one hour of use	Peristaltic Pump Module	PendoTECH	480
pH meter; at user; one hour of use	DP24-PH	pH Panel Meter	3
pH monitor; at user; one hour of use	pH Meter 50 series	Model D-51	10
PMT power supply; at user; one hour of use	PMT Series Linear Precision Modular Supply	Masterflex L/S Digital Drive, 600 RPM, peristaltic pump	40
Printer; at user; one hour of use	Printer consumption	Risolatin average consumption	24,000
Pump; at user; one hour of use	L/S Digital Drive, 600 RPM	Masterflex, pump drive, digital variable speed	750
Reaction unit; at user; one hour of use	STEM Integrity 10 Reaction Station	Alpha Multiservice Inc., holds 10 individual cells	11,000
Recirculating chiller; at user; one hour of use	Polystat Recirculator w/ Force/Suction Pump	Cole-Parmer, Cooling/Heating Circulator, laboratory chiller	5,000
Recorder equipped with range expander; at user; one hour of use	DC6-1-06-10010	Monarch DataChart 6000 Paperless Recorder	120

Meat grinder; at user; one hour of use	Meat grinder	Knife Mill GRINDOMIX GM 200	900
Refrigerator; at user; one hour of use	Two-Door Laboratory Refrigerator/Freezer	Thermo Fisher Scientific, model 18LC-TWW	177
Rotary evaporator; at user; one hour of use	Rotary Evaporator distillation	Ika, RV 8, brushless DC drive motor	500
Sampler; at user; one hour of use	Autosampler	TOC 800 & 900 Autosampler	110
Semi-automated mercury atomic fluorescence analytical system; at user; one hour of use	Lumina 3300	Atomic Fluorescence Spectrometer	1,100
Steam bath; at user; one hour of use	Four-hole steaming bath	Thermo Scientific, PRECISION Concentric Ring Steaming Bath	5,500
Steel cabinet centrifuge; at user; one hour of use	Stainless Steel Compact Cabinet Centrifugal Fan, Industrial Ventilation Fan	Lingdo, Head-Power brand name, Model PWP300	110
Soxhlet extractor; at user; one hour of use	Soxhlet extractor	Soxhlet extractor	1,100
Technicon AutoAnalyzer; at user; one hour of use	Technicon Autoanalyzer	Autoanalyzer 3	455
Timer; at user; one hour of use	Outdoor 7 day digital Timer	Intermatic, Model HB880R	10,000
Tissue homogenizer; at user; one hour of use	Polytron Handheld Homogenizer	Thomas Scientific, Kinematica, Model PT 1200	1,000
Titration; at user; one hour of use	Karl Fischer Moisture Titrator (Coulometric titration)	KEM Kyoto Electronics, main unit, Model MKC-710M	300
Top loading balance; 0.01 g capability; at user; one hour of use	Top Loading Balance	Acom, Model JW-1	1
Turbidimeter; at user; one hour of use	Low Range Turbidimer	HACH, Model 1720E Catalog number 6010018	125
UV-visible photomultiplier (PMT); at user; one hour of use	Photomultiplier Tubes (PMT) Detector	Horiba Scientific, R928 multialkali PMT Ambient cooled side window housing, Model 1911	12,000
Vacuum pump; at user; one hour of use	Vacuum Pump	Laboratory Pump 1/8 HP 220V	60
Variable transformer; at user; one hour of use	Variable Transformer 132V 2A	Staco Energy Products Co, series 200, Panel Mount	240
Water bath; at user; one hour of use	StableTemp Digital Utility Water Baths, 10 liters	Cole-Parmer StableTemp	10,000